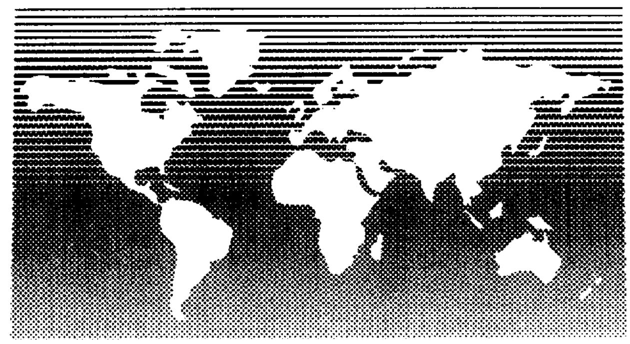
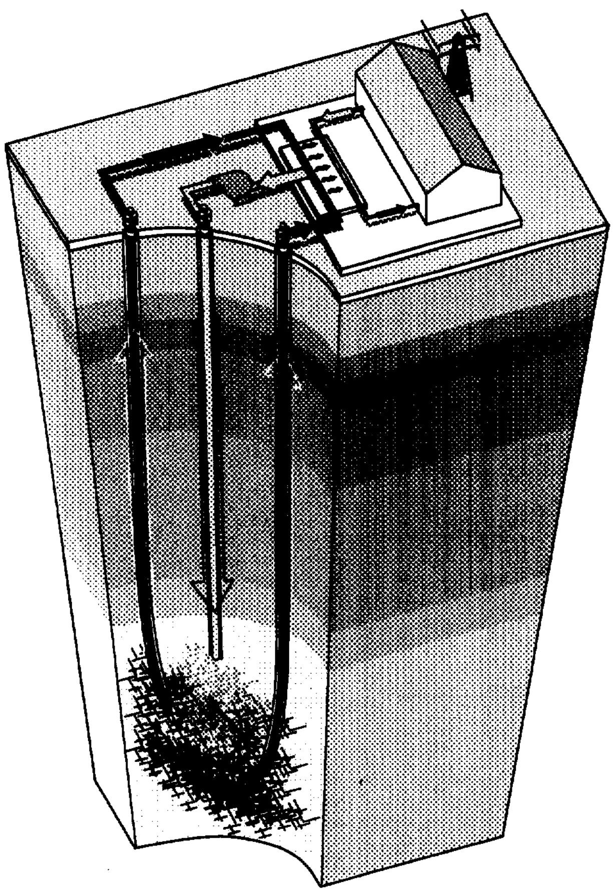
3rd INTERNATIONAL HDR FORUM

MAY 13-16, 1996

SANTA FE, NEW MEXICO USA





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Proceedings

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Other Papers

PREFACE

These proceedings constitute the papers presented at the 3rd International Forum on Hot Dry Rock Geothermal Energy held at Santa Fe, New Mexico on May 13-16, 1996. The 3rd Forum built upon the accomplishments of earlier HDR Forums held in June 1991 at Nurnberg, Germany and in November 1993 at Yamagata, Japan. The 3rd Forum brought together scientists, engineers, and policy makers from 11 countries to discuss the whole range of issues in the development of HDR technology. Reports on recent HDR work in Australia and the potential for HDR development in Armenia attest to the growing interest in HDR geothermal resources around the world.

The technical papers show that the scientific and engineering community has demonstrated in several national programs that the engineered geothermal reservoirs which are the fundamental basis of HDR technology can be created and operatned to extract useful amounts of energy. The wide range of analytical and modeling techniques employed to assess and understand the technical factors associated with the creation and operation of HDR reservoirs is also apparent in the variety of technical papers summarized herein. Overall, these proceedings illustrate how much we know and how much further we need to go to make HDR a practical source of power for the world.

HDR is a widely distributed resource with the potential to supply a major fraction of the world's energy needs in the 21st century. In view of this potential, further development of HDR technology merits a concerted effort for alternative energy applications throughout the world. The 3rd Forum marked another milestone in the cooperative international effort to understand and harness HDR geothermal energy that began many years ago. Hopefully, the collegial spirit and potential for joint national projects reinforced by the forum will help to assure that HDR researchers around the world continue to work together in the years to come.

The 4th International HDR Forum is scheduled to be convened at Strasbourg, France, in the spring of 1998. We hope that all of you will be able to participate.

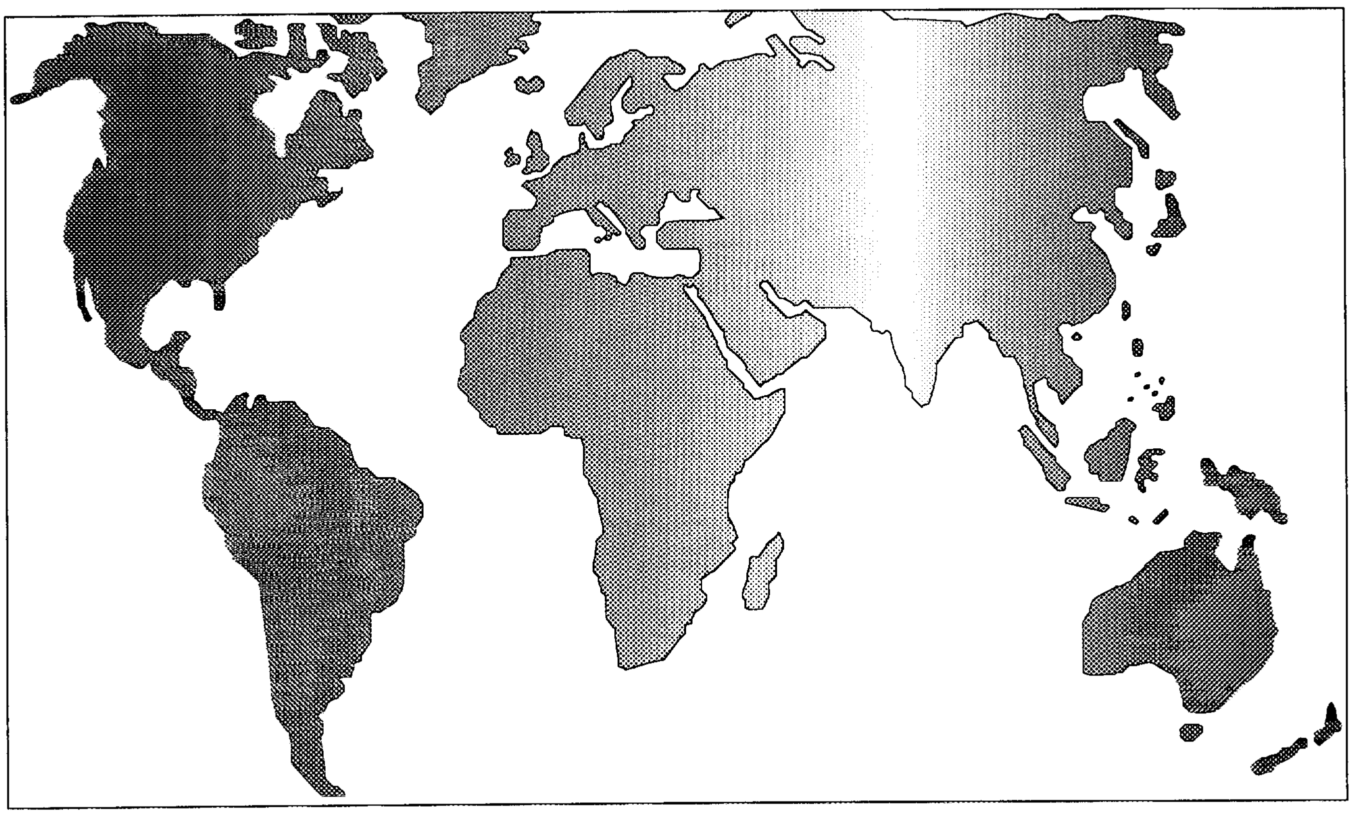
Dave Duchane
3rd International HDR Forum
General Chairman

Paul Kruger
3rd International HDR Forum
Program Chairman

Opening Session

Session Chair:

Paul Kruger



U.S. DEPARTMENT OF ENERGY GEOTHERMAL HOT DRY ROCK PROGRAM

by
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and
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Summary

The Department of Energy (DOE) has supported development of geothermal hot dry rock (HDR) technology for over 20 years, largely under the technical auspices of Los Alamos National Laboratory (LANL).

During that period, researchers successfully demonstrated the technical feasibility of extracting energy from hot dry rock during a number of flow experiments at Fenton Hill, New Mexico, conducted since 1977. These experiments culminated with eight months of testing in 1992-1993 in which steady, uniform heat production was generated at a level of 4 thermal megawatts from a single production well. In 1995, after a two year hiatus, researchers at LANL were able to re-establish these production levels during a two month flow test at the same location. Supporting research on reservoir assessment, instrumentation, modeling and equipment development was also an integral part of the early HDR program, resulting in several spin-off applications that are now being used in other programs.

The success of the Fenton Hill experiments led the Department to issue a competitive solicitation, seeking applicants to deploy the first commercial prototype HDR facility. Since none of the subsequent bids proved acceptable, DOE cancelled the solicitation in October 1995, and announced plans to terminate operations at the Fenton Hill, NM site.

These decisions should not be interpreted as a lack of support for HDR technology or a withdrawal from active research in this area by the DOE. Rather the Department has determined that HDR should become part of the mainstream of geothermal resource development. Consequently, we have begun the process of restructuring the HDR program to include greater involvement by the geothermal industry in a wide range of problems affecting HDR technology.

The Department believes the refocused HDR program will ensure the technology makes a sizeable impact on domestic energy markets in the coming decades. The Department strongly supports HDR technology and believes the resource can provide abundant, clean energy worldwide.

Future Hot Dry Rock Program

In December 1995, at the behest of DOE, the Geothermal Energy Association (GEA) commissioned an industry panel to review the HDR program and make recommendations on the future direction of that program. The panel affirmed the importance of HDR to the future of the geothermal industry, suggested that HDR technology should be integrated into the conventional geothermal industry, and proposed that the name "Hot Dry Rock" be replaced with a new term that would encompass all geothermal resources requiring artificial measures beyond current technology to achieve commercial heat extraction. The panel also made the following recommendations:

- unify management of all geothermal R&D programs and include HDR elements with the unified program;
- convene a panel to formulate short- and long-term geothermal R&D goals, including the long-term commercialization of HDR;
- establish a peer-review committee to evaluate the current status of the U.S. HDR program, publish its findings, and implement technology transfer to move HDR technology into the geothermal mainstream;
- mothball the Fenton Hill site;
- coordinate U.S. geothermal R&D efforts with HDR programs in other countries.

Plans are already underway to implement the panel's recommendations. For example, discussions have begun with two complementary groups to help set the course of future HDR work. One panel would examine technology needs for fracture identification and mapping. The second group, more industry oriented, would address HDR in the context of its relationship to conventional geothermal industry. Other plans include:

- issuance of a Program Announcement later this fiscal year or early next year to solicit proposals from stakeholders for projects that would help advance the state-of-the-art of HDR technology;
- participation in two or more tasks under a proposed International Energy Agency Agreement on geothermal energy;
- decommissioning or transfer of the Fenton Hill, NM hot dry rock site;
- a final report, archiving the Fenton Hill, NM hot dry rock research results for use by interested stakeholders;
- development of a five year plan for technology improvements needed by the industry to have more confidence in the technology.

In summary, the Department is committed to bring hot dry rock technology into the marketplace as a viable energy option. The resource is virtually unlimited with no emissions of greenhouse gases or other adverse environmental effects. Furthermore, when commercially available, the technology can be adapted for small power plant applications in remote locations. In brief, HDR has the potential to make very substantial contributions to the world's energy economy in the next century.

Evaluation of Hot Dry Rock Resources in Japan

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The amount of HDR resources was estimated on the basis of temperature data along wells and geological conditions. New Energy and Industrial Technology Development Organization (NEDO) has promoted Geothermal Development Promotion Survey Project to survey conventional geothermal resources. NEDO has drilled 195 wells in 29 regions. Fig. 1 shows these 29 regions. As the results indicates that there are potential areas for hot dry rock in these areas, we decided to evaluate HDR resources using NEDO's data.

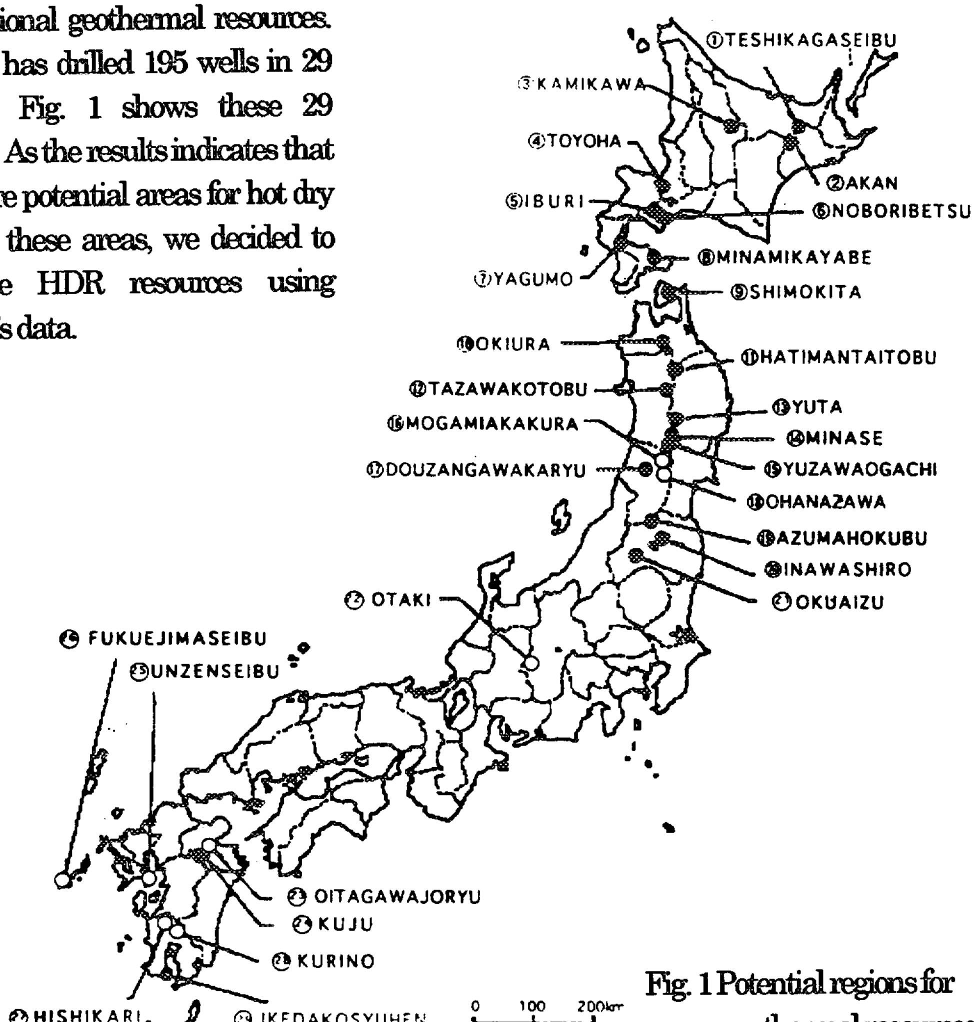


Fig. 1 Potential regions for geothermal resources.

First, wells which were drilled down to 1,000m or deeper were selected. 177 wells out of 195 wells were drilled deeper than 1,000m. To distinguish the hot dry rock resources from conventional geothermal resources, we picked up the areas where the heat is transferred not convection but conduction. For this purpose, the temperature of wells increases linearly more than 500m at the bottom of wells were selected. 141 wells out of 177 wells satisfied this condition. Then, 59 wells having an estimated temperature of 250 °C or lower at the depth of 3 km were excluded from 141 wells. As shown Fig.2, the temperature of along these wells is extrapolated linearly to the depth of 5km. We define that the reservoir from the depth where rock temperature is 250 °C to 3km as shallow reservoir, and from 3km to 5km as deep reservoir. Under-ground structure model was constructed using temperature data of 82 wells, geologic structure and volcanic activities in each region. The area surrounded by the circle in Fig.3 indicate the example of the potential area for hot dry rock at Yakumo region in Hokkaido. Fig. 4 illustrates the surface area and shallow and deep reservoir of HDR. We estimated volume and average temperature of shallow reservoir and deep reservoir for 18 promising hot dry rock regions. The amount of energy of hot dry rock resources in these regions can be estimated by the volume and average temperature of the reservoir, and density and specific hear of rock.

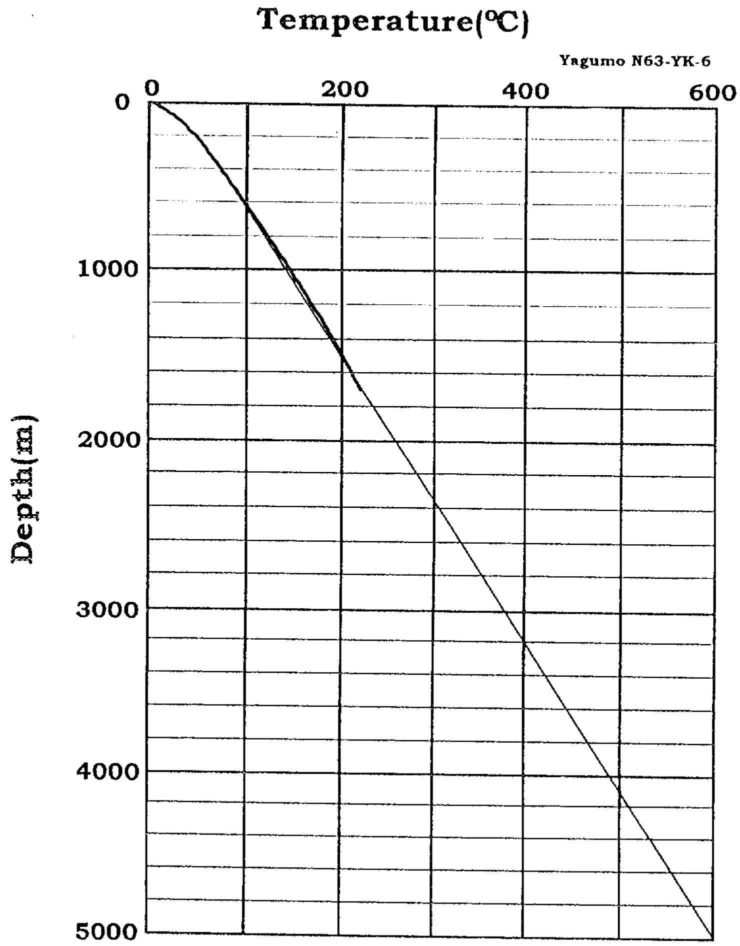
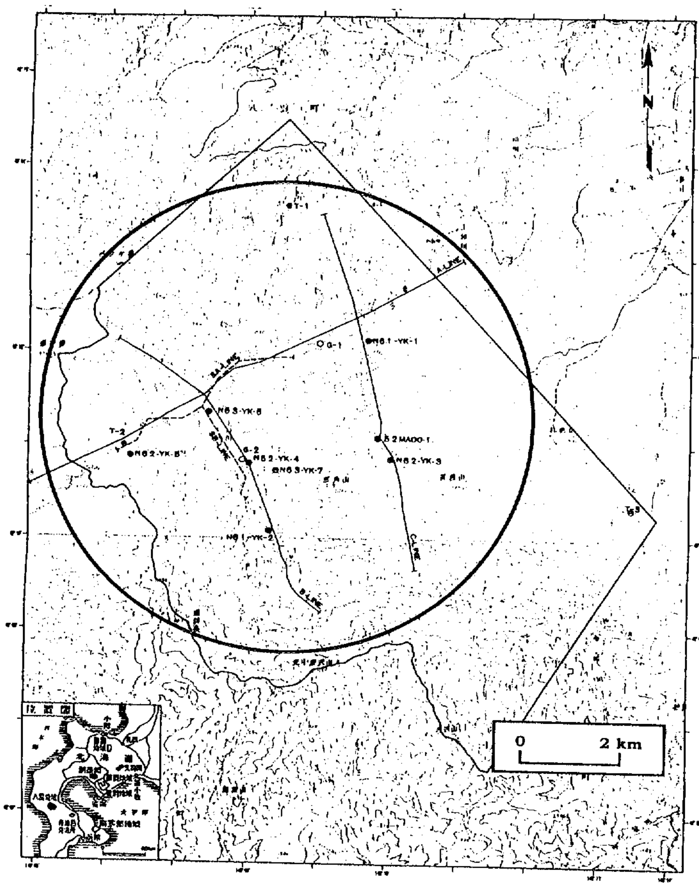


Fig.2 Temperature distribution measured and extrapolated along well

Then, the amount of electricity produced from hot dry rock was estimated from these data by assuming that 3% of thermal energy could be converted to electric energy because of



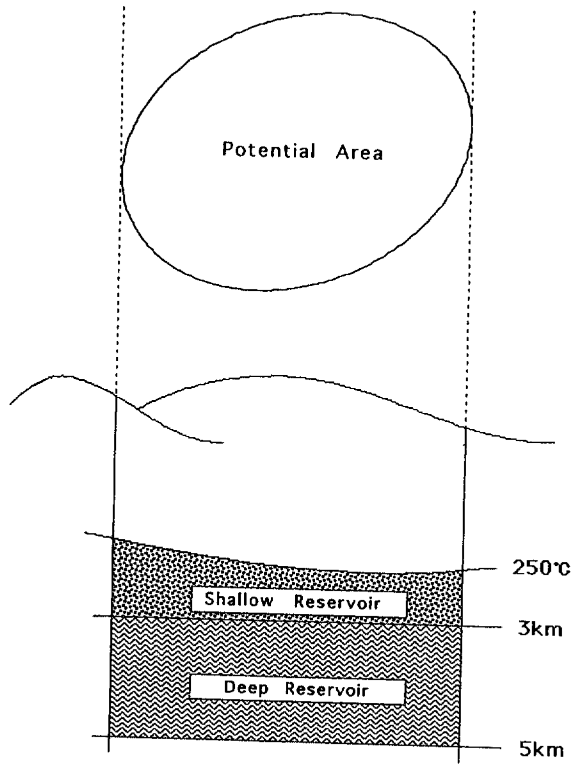


Fig.3 Potential area for hot dry rock resources

Fig.4 Images for HDR reservoir

Table 1 indicates the electricity produced from each region for 20 years. If rock whose temperature is more than 250 ℃ can be available for producing electricity from hot dry rock, about 28,910MW of electricity is estimated to be produced for 20 years from shallow resources and about 98,140MW from deep resources. Seven regions including Akan, Yagumo, Eastern Hachimantai, Minase-Yuzawaogachi, Inawashiro, Toyoha and Kuju are regarded as promising areas.

Table 1. Estimated Amount of Electricity from HDR (for 20 years)

Name of Locations	Area km^2	Shallow Reservoir	Deep Reservoir
		Depth of 250°C ～ 3 km (MW)	3 km ～ 5 km (MW)
West Teshikaga	18	10	1,260
Akan	139	5,120	15,690
Kamikawa	79	1,670	7,680
Toyoha	66	1,860	6,630
Iburi-Noboribetu	58	460	4,510
Yakumo	82	2,920	8,590
Minamikayabe	25	340	1,920
Shimokita	73	1,430	5,280
Okiura	26	430	2,020
East Hachimantai	66	2,610	7,200
East Tazawa Lake	67	170	4,700
Yuda	3.5	40	260
Minase-Yazawaokachi	129	5,950	12,960
Dozankawa Karyu	35	600	3,020
North Agatsuma	32	640	2,630
Inawashiro	51	2,050	5,300
Okuaizu	49	1,460	4,290
Kuju	40	1,150	4,190
Total		28,910	98,140

A European View of the Development of Hot Dry Rock Geothermal Systems

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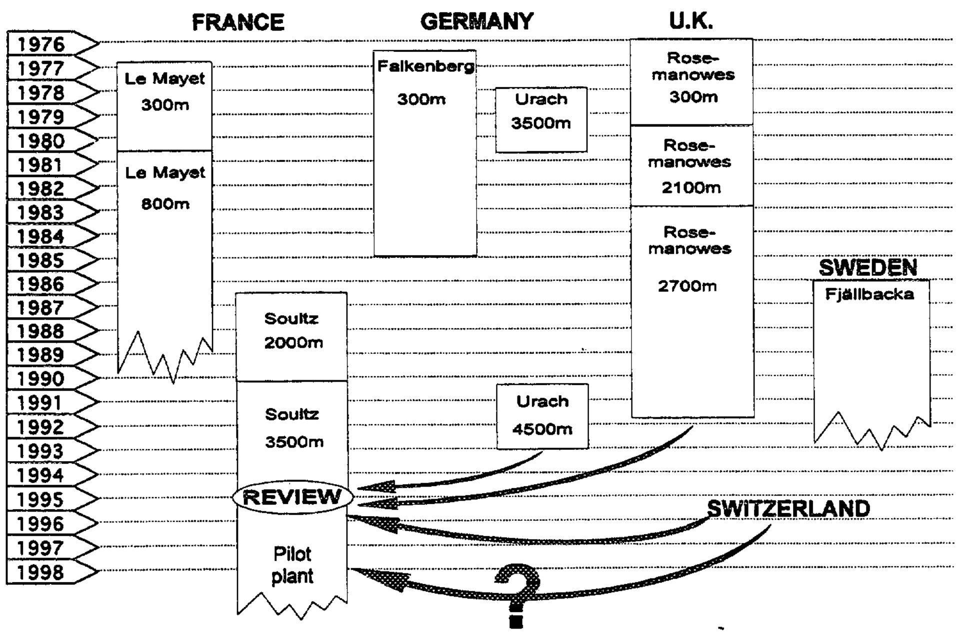
Hot Dry Rock (HDR) geothermal research and development has been underway in Europe since 1973. These investigations have been conducted entirely in granite at depths as great as 4000m but with temperatures of less than 200°C. HDR work is now focused at one site, Soultz-sous-Forêts, near Strasbourg in France; it is supported by France, Germany and the European Commission. There is less formal support from both Italy and Switzerland. The technical progress at Soultz will be reported by other authors at this conference; my paper is directed more towards the underlying philosophies and views of the future of HDR operations in Europe.



There is an underlying measure of confidence in the 'European' view of HDR that stems from the conclusions of the work over the last 20 years. On the practical side, the drilling history in Europe has been one of success, approximately five holes in various HDR projects have reached 2500m to 4000m in granite with reasonable progress and manageable cost. While it can be argued that none of the experience has had to deal with extremes of temperature, this record has reduced the uncertainty associated with the drilling process itself. Similarly, the borehole geophysics tools for reservoir characterisation have been developed to the point where reliable operational performance can be obtained, albeit for restricted periods.

The key step forward has been the acceptance of the view that the interconnection of boreholes over interwell distances of commercial interest occurs through the pre-existing network of fractures, faults and joints of hydraulic significance. The apertures of the flowpaths or channels within the interconnected fractures may be modified by both stimulation and circulation but the basic geometry is controlled by the pre-existing natural conditions. Several important points concerning HDR development stem from this conclusion:

1 Success in HDR systems will rely on finding fracture networks that are well connected with fracture apertures that can provide the effective heat transfer areas within suitably large volumes of hot rock. Almost by definition, these systems will be 'open' to the 'far field'. Exploitation of such systems will need to follow the conventional hydrothermal practice of multiple production wells per injection well with downhole pumping or flashing on the production side.

2 The nature of the interconnections between wells will be controlled by the orientation of the natural fractures and their relationship to the in-situ stress field. It is anticipated that most systems will exhibit a strongly preferred flow direction based on the combined anisotropy of the stresses and the fractures. However, the individual borehole trajectories and completions into a fracture network will be a major influence on the overall reservoir performance.

3 Hydraulic stimulation by injecting at high pressure and flow rate is needed to enhance the connections to the natural fractures in both the injection and production wells. Currently there is insufficient experience to conclude that fracture apertures in open systems need to be enlarged at great distances from the wells by the injection of large volumes of fluid.

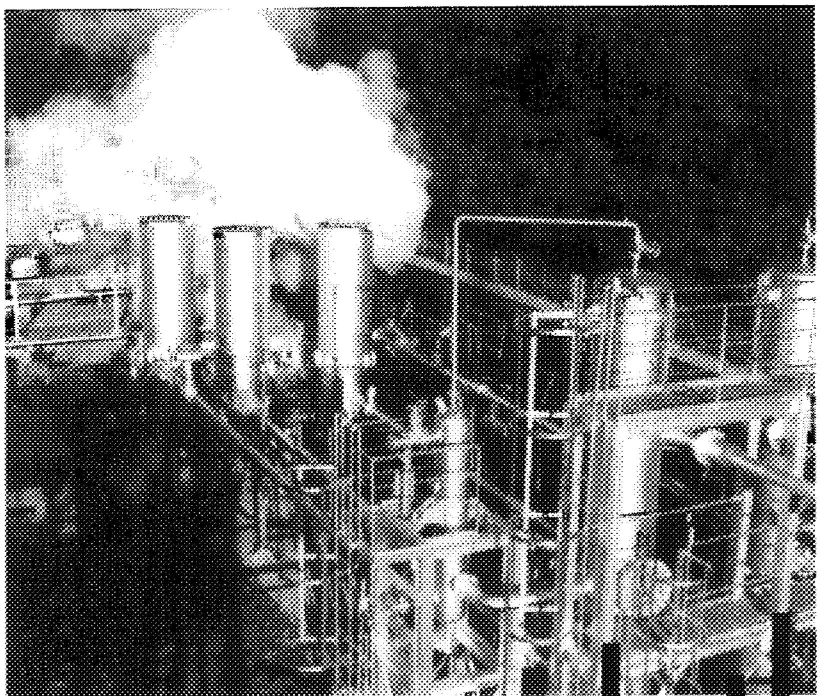
4 The optimum prospective sites for HDR development today are those known to be associated with fracture controlled thermal anomalies extending into the crystalline basement. These could be regions associated with existing geothermal exploitation, major graben features, ancient volcanism or substantial deep seated fault systems.

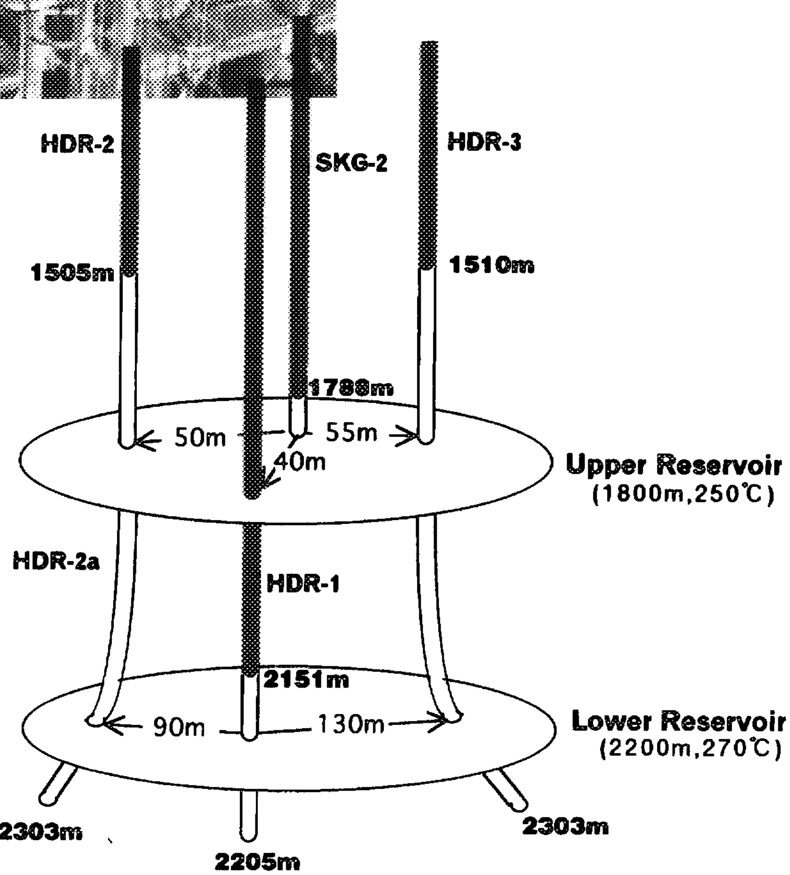
There is no direct exploration technique that can confirm the existence of such 'suitable' fracture systems without drilling to full depth so, currently, there is no method to pre-assess the land area of Europe that may support HDR systems. However, considerable data is available for central Europe from past drilling activities which would need to form the basis of such an evaluation. For example, the European programme at Soultz is located in the Rhine Graben which is well documented historically through oil and gas exploration to 3000m in some areas.

HDR progress will be made through understanding the management and development of such open systems. There may well be better sites in Europe that have yet to be identified but Soultz certainly has the prospect of being able to support a pilot plant through collaboration both internally and worldwide. It is clear that this type of HDR system in an open, fractured structure is similar in most respects to the exploitation of a natural hydrothermal reservoir. Progress in developing such HDR systems will also be of benefit at the margins of hydrothermal fields thus expanding the overall application of all forms of geothermal energy when it is successful.

Session 2:
Hijiori I

Session Chair: Fritz Rummel





Review of procedures of HDR reservoir creation at Hijiori from design methodology

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Design methodology for man-made geothermal reservoir

HDR reservoir creation procedures at the Hijiori HDR test site were reviewed from design methodology for the man-made geothermal reservoir proposed by Abé and Hayashi. They summarized design steps to create a subsurface heat exchange system as follows: 1) to select the target point, to estimate the characteristics of the fracture that will be made and to design an injection well; 2) to correct the first objectives by logging the injection well and to design hydraulic stimulation; 3) to correct the second objectives by AEs mapping during stimulation and logging after the stimulation, and to design production well(s); 4) to correct the third objectives and to characterize the reservoir by logging, injection tests and so on. The purpose of the methodology is to increase certainty of characteristics of a man-made reservoir by data feedback and re-interpreting the characteristics.

Examination of procedures to make the 1800-m-deep reservoir at Hijiori

In 1984, Hijiori was selected as the HDR test site because the well, SKG-2, had been drilled to 1,804 m and had a high bottom hole temperature. Conditions of SKG-2 were as follows: 1) Open hole section was from 1,298 m to the bottom; 2) The top of basement rock was 1,460 m; 3) Lost circulation points existed from 1,500 to 1,700 m. In 1985, as to make a reservoir in the basement rock by full hole pressurizing, 7-inch casing pipes were set to 1,788 m. In 1986, water was injected into SKG-2 to make an 1800-m-deep reservoir. Reviewing from the design methodology, creation of the 1800-m-deep reservoir was started from step 2 without sufficient pre-estimation of reservoir characteristics.

At step 3, target of a production well, HDR-1, was discussed based only upon AEs mapping. In 1987, HDR-1 was drilled into the AEs cloud to the south of the injection well. However, an injection test in 1988 showed that the connection through the 1800-m-deep reservoir between SKG-2 and HDR-1 was poor. Afterwards, AE maps were re-calculated more accurately by increasing AE sensors and powder explosions at the bottom of SKG-2, and the azimuths and dips of fractures were measured by BHTV and oriented coring. These data were interpreted as low-impedance planes lying at the open hole section of SKG-2 in a west-east direction with a high-angle dip to the north.

In 1989, the second production well, HDR-2, was drilled to the west of SKG-2. Impedance between SKG-2 and HDR-2 was low and water loss during circulation was decreased. It was confirmed that the dominant direction of water flow at the 1800-m-deep reservoir was west-east and consistent with the azimuth and dip of pre-existing fractures at Hijiori test site. In 1990, the third production well HDR-3 was drilled to the east of SKG-2, and the connection between SKG-2 and HDR-3 was good as had been expected.

At the 1800-m-deep reservoir, the steps 3 and 4 were carried out three times. By these trials, certainty was increased and water loss was decreased year by year. To estimate dominant direction of flow through a man-made geothermal reservoir, azimuths and dip of faults around the site, in-situ stresses, azimuth and dip of fractures open to wells and AE locations should be examined carefully.

Table 1 History of the 1800-m-deep reservoir

86	Stimulation by injecting water into SKG-2.
87	Drilling of HDR-1 to 1,805 m.
88	Flow test between SKG-2 and HDR-1, and deepening of HDR-1 to 2,205m.
89	Drilling of HDR-2 to 1,910 m, and one-month circulation between SKG-2 and HDR-1, HDR-2.
90	Drilling of HDR-3 to 1,907 m.
91	Three month circulation between SKG-2 and HDR-1, HDR-2, HDR-3.

Examination of procedures to make the 2200-m-deep reservoir

Creation of a deeper reservoir under the 1800-m-deep reservoir was discussed in 1988. The depth of the deeper reservoir was decided around 2,200 m as to prevent interaction of flow through the both reservoirs.

In addition, an injection method though drill pipes connected with PBR was selected because it had been operated successfully at Fenton Hill and strength of open bole packers were estimated as insufficient for stimulating pressure.

In 1992, a 2200-m-deep reservoir was made under the 1800-m-deep reservoir by injecting water into the open hole section from 2,159 to 2,205 m of HDR-1. The maximum injection rate was planned as 100 l/s, and wellhead pressure at the maximum rate was estimated as 25 MPa. Friction reducer was used because water was injected through 5-inch-diameter drill pipes. However, at the flow rate of 70 l/s, wellhead pressure reached 25 MPa. Thus, flow rate could not be increased. AE hypocenters during the stimulation distributed around planes that spread to the east and west of the injection well and declined to the north at high angle. Fractures open to HDR-1 were measured by BHTV, and oriented cores and their dominant azimuth and dip were consistent with AEs mapping.

In 1993, HDR-3 was deepened to 2,300 m. The section from 1,500 to 2,300 m remained open because it could be used as a production well for both reservoirs. Distance between HDR-1 and HDR-3 at the 2200-m-deep reservoir was planned as over 100 m that was about twice of distance between injection well and production ones at the upper reservoir. Based on AE mapping of the 1992 stimulation, BHTV logging, and oriented cores of HDR-1, azimuths and dips of probable fracture planes were expected. The depths where the deepened HDR-3 penetrated the planes were calculated from 2,095 to 2,236 m. By PTS logging during preliminary circulation test in 1995, a fracture of the largest inflow in HDR-3 was detected from 2,188 to 2,200 m. While deepening HDR-3, water level of HDR-1 was monitored and three oriented coring operations were carried out as the level increased. In one of the cores, an open fracture was found and its azimuth and dip were similar to the supposed plane.

In 1994, HDR-2 was deepened to 2,300 m. Based on the testing of HDR-3, probable fracture planes were estimated using the above-mentioned data in conjunction with BHTV and oriented-core data from the deepened HDR-3. With this information, the trajectory of HDR-2 was selected so that the distance between HDR-1 and the deepened HDR-3 was about 100 m. The depth where the deepened HDR-2, we call it HDR-2a afterward the deepening, penetrated the planes was calculated from 2,094 to 2,194 m. By the preliminary circulation in 1995, depth of the largest inflow in HDR-2a was around 2,165 m. Although there were differences between predicted depth and actual ones, these predictions and confirmations were essential to design the subsurface circulation system.

Preliminary circulation test of the 2200-m-deep reservoir conducted in 1995 showed that dominant flow direction in the reservoir was east-west similar to that in the upper reservoir.

Table 2 History of the 2200-m-deep reservoir

92	Stimulation by injecting water into HDR-1
93	Deepening of HDR-3 to 2,303 m.
94	Deepening of HDR-2 to 2,302 m.
95	Preliminary circulation test between HDR-1 and HDR-2a, HDR-3 for 25 days.

Conclusion

Achieved level at Hijiori estimated by the design methodology are summarized as follows.

1) Two reservoirs were created at Hijiori by full hole pressurizing. However, flow impedance of each reservoir after the first stimulation was not low, estimations of flow rate and wellhead pressure during the stimulation were not adequate, nor geometrical dimension of the reservoir could not be pre-estimated.

2) The dominant direction of flow was predicted by the azimuths of the faults around the site, those of the fractures open to the wells and the distribution of AEs hypocenters, and water loss was reduced by drilling the production wells to the direction of the injection wells. However, distances between the injection wells and the production wells could be longer because the farthest AEs located about 500 m distant form the injection wells.

Review of the reservoir creations at Hijiori showed importance of the design methodology to increase certainty by data feedback and re-interpretation of reservoir characteristics. The methodology should apply not only reservoir creation but also improving circulation system.

Reference

Abé, H. and Hayashi, K., Fundamentals of Design Concept and Design Methodology for Artificial Geothermal Reservoir Systems, GRC Bulletin, May 1992

Hijiori Deep Reservoir Stimulation, Drilling and These Results

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Abstract

In FY 1992, NEDO started to develop the Hijiori deep reservoir after success of the shallow reservoir circulation test in FY 1991. The target depth is 2,200 m of which temperature is about 270°C.

In FY 1992, hydraulic fracturing was carried out in HDR-1 whose open part is from 2,150 m to 2,200 m, and PBR (Polished Borehole Receptacle) was used to isolate the deep reservoir from the shallow reservoir.

In this fracturing, total 2,115 m^3 water was injected with 4.3 m^3/min. of maximum flow rate and 255 ksc of maximum pressure. Well head pressure of HDR-2 and HDR-3 was monitored and any pressure change was not observed while fracturing. In the open hole zone, five fractures were confirmed by PTS logging and BHTV during and after the hydraulic fracturing operation. And a lot of AE events were observed and its direction was mainly west-east.

In FY 1993, HDR-3 was drilled from 1,900 m to 2,300 m to penetrate the deep reservoir. The well trajectory was planed to have over 100 m distance from HDR-1 on the eight fracture planes, which were assumed from AE events, BHTV and others. While HDR-3 drilling, HDR-1 water level was monitored and we could successfully get the orientated cores including artificial fractures. The connection between HDR-1 and HDR-3 through the deep reservoir was satisfactory.

In FY 1994, HDR-2 was drilled with side-tracking from 1,600 m to 2,300 m. The well trajectory was planed on the same way as HDR-3, but only three fractures were considered by the result of HDR-3 drilling. Also HDR-1 water level was monitored while drilling, then the orientated cores including fractures were taken. The connection between HDR-1 and HDR-2 through the deep reservoir was confirmed, too.

Thus we succeeded to make the artificial deep reservoir and circulation system. Then, the Preliminary Circulation Test (PCT) for the Hijiori deep reservoir was conducted in FY 1995.

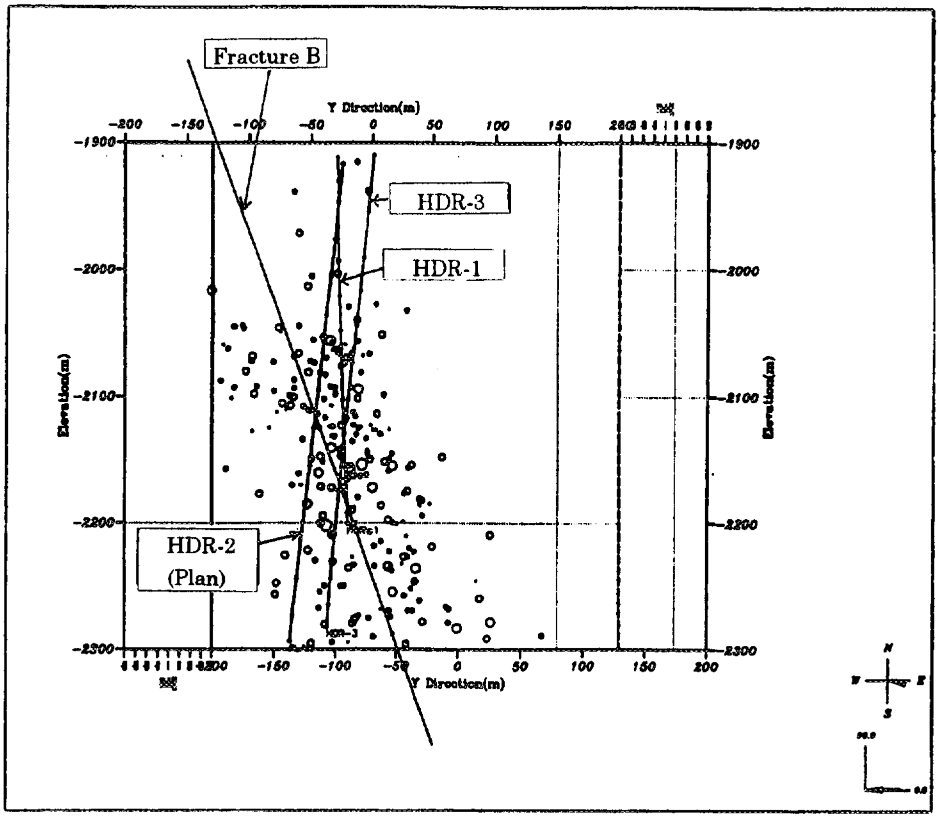

Fig. 1　Plan of the HDR-2 trajectory (1)

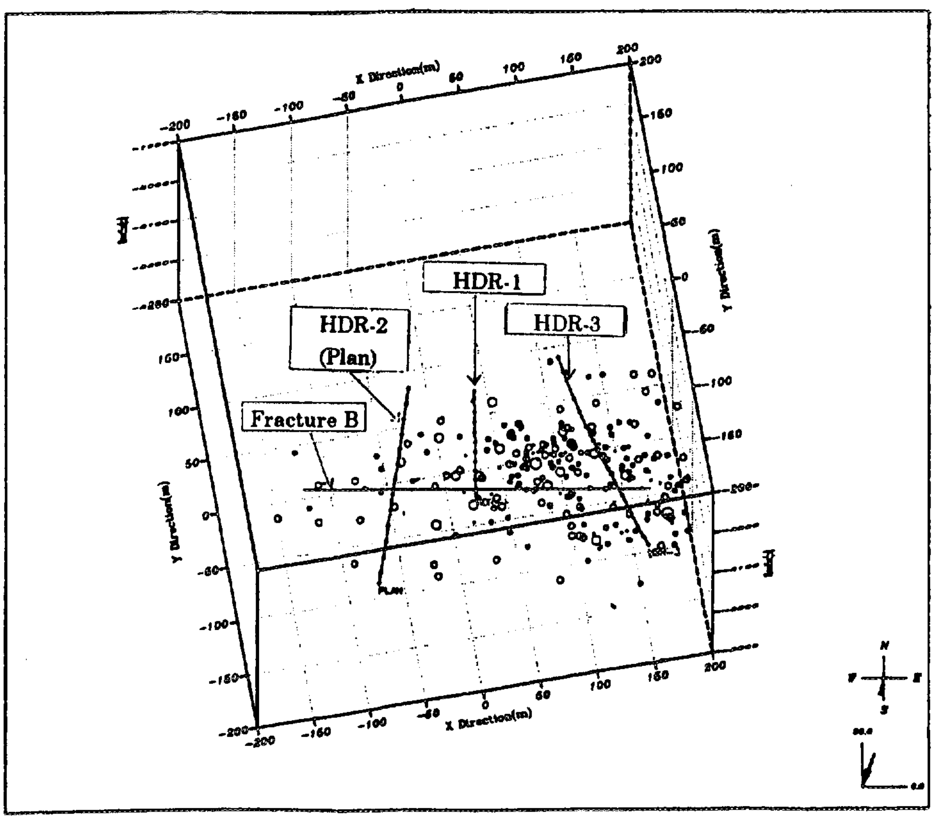

Fig. 2　Plan of the HDR-2 trajectory (2)

Characterization of Effective Fractures by Downhole Measurements at Hijiori HDR Test Site

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Introduction

In FY1995, a preliminary circulation test of a deep reservoir where the injection interval was from 2150m to 2200m depth of HDR-1 was conducted with two production wells, HDR-2a and HDR-3. The PTS (Pressure-Temperature-Spinner) well logging during the circulation test identified about 10 feed zones in an openhole interval from 1500m to 2300m. We discuss the dynamic and static characteristics of these effective fractures based on the PTS well log data.

Identification and classification of effective fractures

Effective fractures were identified by spinner and temperature anomalies of PTS log data and classified into 10 effective fractures as shown in Fig.1. Furthermore, these fractures were compared to those which had been identified in the 90 days shallow reservoir circulation test where the injection interval was from 1788m to 1802m depth of SKG-2 with three production wells, HDR-1, HDR-2 and HDR-3, then fracture No.1 to 5 classified into the shallow reservoir and No.6 to 10 classified into the deep reservoir.

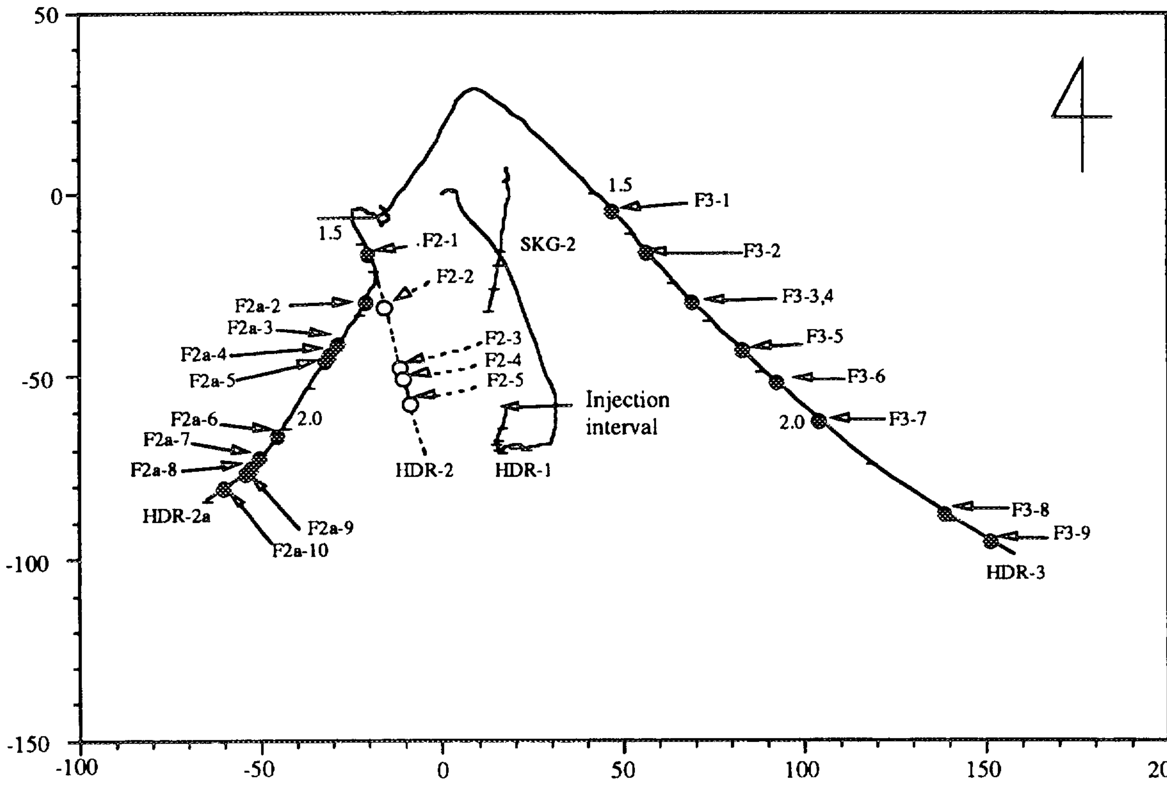

Fig.1 Effective fractures on a plane view of well trajectories

Quantitative characterization of effective fractures

We calculated flow rate and temperature of produced water from each effective fracture by using PTS well log data, and investigated characteristics of effective fractures based on these calculated values. Fig.2 shows the relation between the flow rate from the shallow reservoir and the pressure at 1500m depth of the production wells. It is found that the flow rate from the shallow reservoir is well correlated to the outlet pressure inside the production well like a draw down of petroleum reservoir. It means the pressure of the shallow reservoir is kept almost constant in spite of the variation of the injection pressure. It is inferred that the shallow reservoir had been well developed by the 90 days circulation test in 1991 and have a large volume, then the variation of the injection pressure does not affect directory to shallow one. From Fig.2, we can say that the productivity index is 1.10 l/sec/Mpa in HDR-2a and 1.73 l/sec/Mpa in HDR-3, and the reservoir pressure of HDR-3 is less than HDR-2a, which consist with an extension of fractures and water loss to the east. Fig.3 shows the relation between the flow rate from the deep reservoir and the well head pressure of the injection well. We can see a good correlation between them. From Fig.3, the flow impedance are estimated to be 2.53 Mpa/l/sec in HDR-2a and 3.96 Mpa/l/sec in HDR-3.

Estimation of plane fracture

The behavior of the fractures belonging to the shallow reservoir were well known by the shallow reservoir circulation test in 1991, and it is inferred that the fractures which have same fracture No. belong to the same fracture plane. The new side tracked well, HDR-2a made it possible to estimate dip azimuth and dip angle of plane fractures in shallow reservoir. The result was around -16 and 74 degrees for F2, -15 and 73 degrees for F3, -16 and 73 degrees for F4, and 4 and 66 degrees for F5. These results are consistent with the result of fracture analysis of BHTV data and fracture mapping result of microseismic data. As for the deep reservoir, the term of the circulation test was too short to correlate fractures each other.

Conclusion

By classifying each effective fracture into the shallow and the deep reservoir, both of reservoir were well characterized. This kind of analysis can not be performed by using surface data, because we can not distinguish whether produced fluid come from the deep or the shallow reservoir by using only surface data, and because a well head pressure does not reflect borehole pressure due to flushing of hot water inside well. The plane fractures of the shallow reservoir are almost parallel, and F3 and F4 which were most productive in the shallow reservoir circulation test intercept injection interval of SKG-2 .

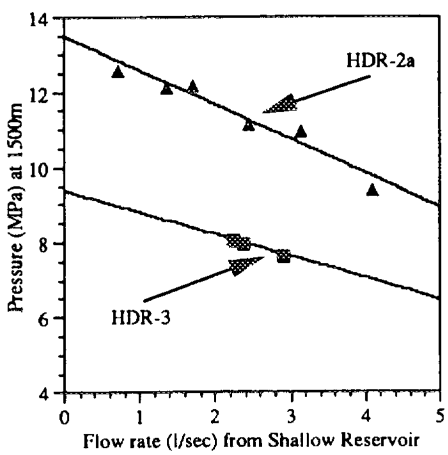

Fig. 2 The shallow reservoir

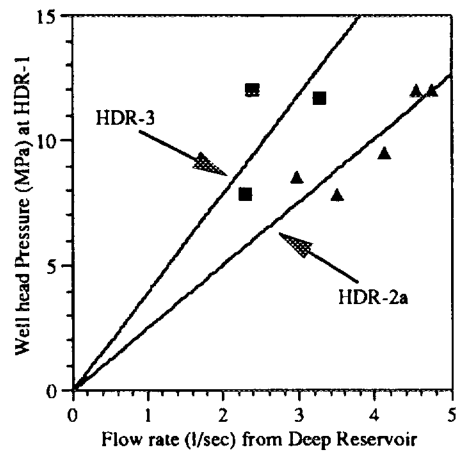

Fig. 3 The deep reservoir

Estimation of In-Situ Stress State at Hijiori Test Site

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A direction of in-situ stress is one of the key factors which controls the direction of man-made fractures in developing Hot Dry Rock system. At Hijiori test site, 1,800m-depth and 2,200m-depth fractures were made by hydraulic fracturing. The test site is located at south rim of the Hijiori caldera. Both fractures were almost parallel to each other, and inclined steeply toward north, i.e. to the center of the caldera. The authors summarize the in-situ stress state at Hijiori test site estimated from macro-scopic point of view (tectonic earth stress) to micro-scopic laboratory test (DSCA analysis). The phenomena and/or research which were investigated are listed as follows.

A. Relative movement of ground surface (Sato, H.,1994)
   A relative movements were measured by trigonometrical survey in Tohoku area to estimate the global stress state in this area.
B. Geological survey of Hijiori caldera
   The stress state could be estimated from dips and strikes of faults associated with caldera(NEDO,1992).
C. Overall tendency of micro-seismic (AE) cloud (NEDO,1990)
D. Focal mechanism solution of AE events (Sasaki,S.,1993)
E. Geometrically fitted plane to injection and production points (NEDO,1992)
F. Natural fractures observed by BHTV in HDR-2/3 (NEDO,1992)
G. Hydraulically made fracture observed by BHTV in SKG-2
H. Mapping of open fractures by micro-scopic observation on core specimen (NEDO,1992)
I. The Kaiser effect observed during compression test of core (NEDO,1990)
J. Mapping of shear fractures by micro-scopic observation on core specimen (NEDO,1992)
K. Differential Strain Curve Analysis (Oikawa, Y.,1993)

Table 1 Estimated direction of maximum and minimum principle stress

Method / Phenomena	Type	Direction of principle stress	
		Maximum	Minimum
A. Trigonometrical survey	2-D	E-W	N-S
B. Geological survey	2-D	E-W	N-S
C. AE cloud	3-D	E-W ～ ENE-WSW	N-S ～ NNW-SSE
D. Focal mechanism solution	3-D	N79E	N189E
E. Injection/production points	3-D		N166E20S
F. BHTV-natural joints	3-D		N-S
G. BHTV-hydraulic fracture	3-D		N-S
H. Core observation-open fracture	3-D		N-S
I. AE - Kaiser effect	2-D	N68.5W	N21.5E
J. Core observation-shear fracture	3-D	Vertical	NE-SW or NW-SE
K. DSCA - HDR-3	3-D	E-W	N-S

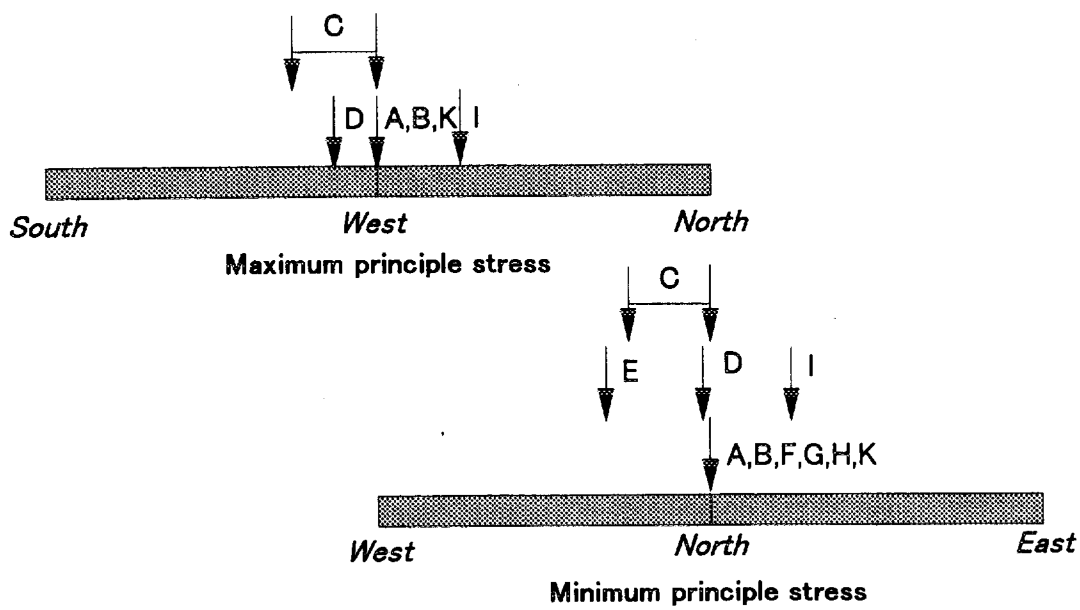

Figure 1 Direction of principle stress

Reference

S. Sasaki;CRIPIE report, (1993)

Sato H,:J. of Geophy.Res., Vol.99 p22261-22274, (1994)

NEDO; HDR project annual report, 1987～1995

Oikawa, Y. et al.:J. of Mining and Materials, Vol.111 p587-594,(1995)

Downhole Monitoring of Induced Seismicity During a Preliminary Circulation Test at Hijiori HDR Test Site

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An active induced seismicity was observed during a 30-day preliminary circulation test at Hijiori HDR test site in 1995. A double sondes system and a high temperature 3-component geophone sonde were installed in well SKG-1 and well SKG-2 as temporally stations in addition to the permanent surface network. The downhole stations have the advantages of good sensitivity to detect small seismic signals and of good qualities of signals which are less affected by heterogeneity of shallower sedimentary rock. Figure 1 shows the schematics of monitoring network. Because of the high temperature environment around the geophone in SKG-2 (200℃), the observation period of the downhole system was restricted to only the well stimulation period which was conducted at an early stage of the circulation test. During the well stimulation period, about 1,400 events were recorded by the downhole monitoring system.

Figure 2 shows a concept of the triaxial double sonde method (Tezuka and Miyairi, 1995) which requires one source azimuth and more than three onset times (either P wave or S wave) to calculate source locations. The source locations estimated by this method are shown in Figure 3. The global feature of the seismic cloud, which has a trend spreading east-west and dipping to the north, is similar to the cloud observed during the hydraulic fracturing in 1992 (Figure 4). But, the range of the cloud becomes wider and relatively large magnitude events are seen at the edge of the cloud. Other characteristic features are two dense dipping clusters which can be seen in the north - south cross section. In the location map of the hydraulic fracturing in 1992, there is no seismic event at the lower cluster part, while a similar dense cloud can be seen at the upper cluster part. The lower cluster is supposed to show an area where the new artificial reservoir was created by this well stimulation test.

The seismic events can be also classified into some groups by taking S to P wave amplitude ratios. Incidentally, it was found that the group with large S wave signal corresponded to the upper cluster, and the group with small S wave signal corresponded to the lower cluster. These facts suggest an understanding that the two clusters represent different fractures which might be activated by different focal mechanisms.

Reference

Tezuka,K. and Miyairi, M., 1995, AE monitoring with triaxial double sonde method at Hijiori HDR test site, Geotherm. Sci & Tech., Vol.5 pp.3-20

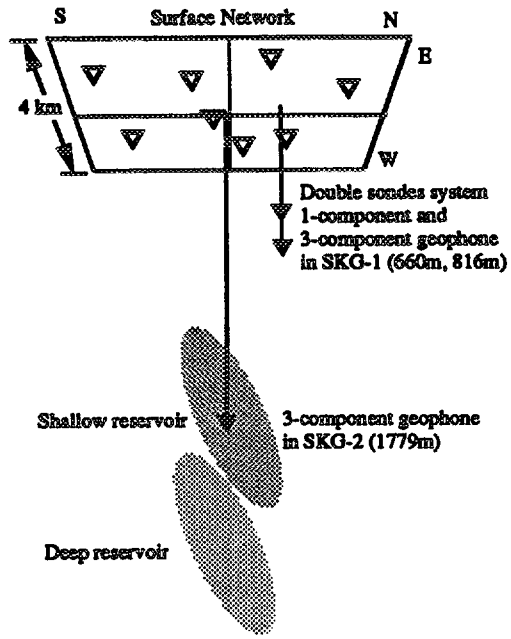

Fig. 1: Microseismic monitoring network at Hijiori HDR test site
▽: Surface stations
▼: Downhole stations

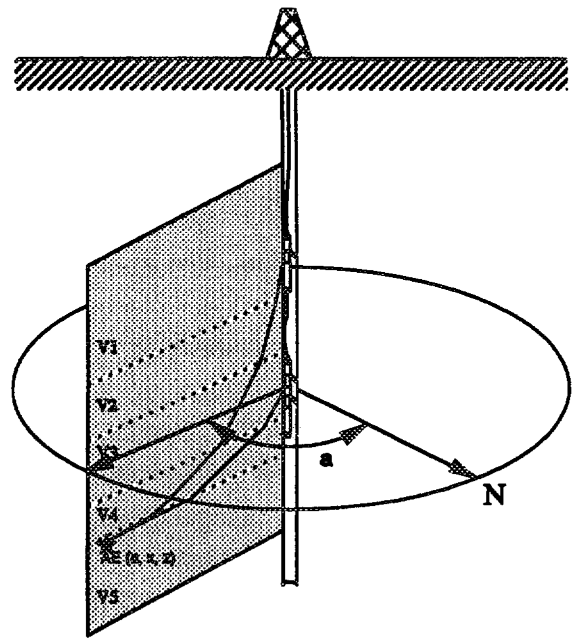

Fig. 2: Concept of triaxial double sonde method
a: source azimuth
x,y: Coordinate in vertical plane defined by source azimuth a

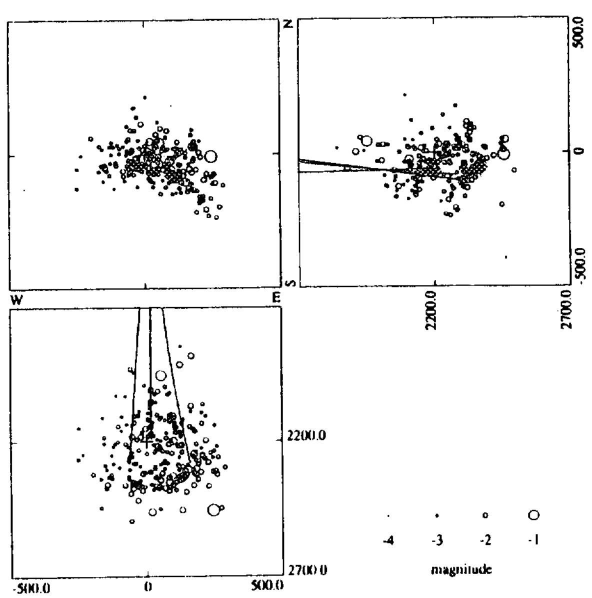

Fig. 3: Source locations of microseismics observed during the preliminary circulation test in 1995 (only the period of well stimulation test)

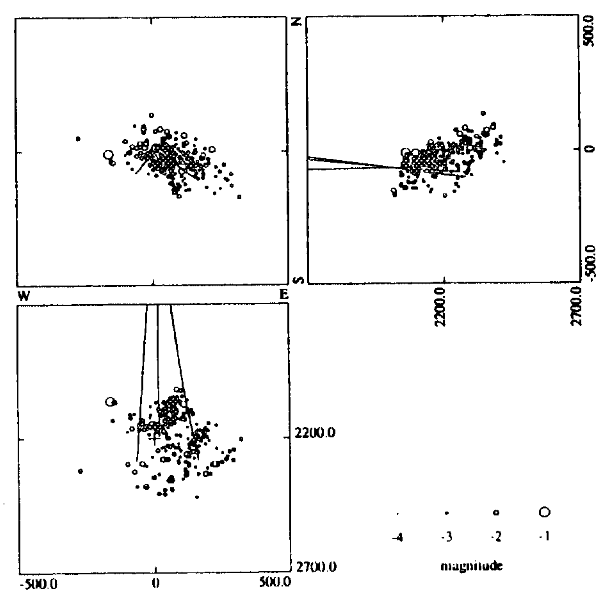

Fig. 4: Source locations of microseismics observed during the hydraulic fracturing in 1992

Characteristics of microearthquakes accompanying the 1995 circulation test at the Hijiori HDR site, Yamagata, Japan

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NEDO conducted a 30 day circulation test at Hijiori HDR site for about one month from August 6 to 30, 1995. A total of 51,500 m^3 of water were injected into an injection well(HDR-1) at an average flow rate of 1 m^3/min and over 120,600 m^3 of water was returned from two production wells(HDR-2,HDR-3).

Microseismicity accompanying the circulation test was monitored by a network of ten surface seismic stations deployed at an average distance of 2 km from the injection well.

The relations among the microseismic event rate, the amount of water injected into HDR-1 and the well-head pressure during the circulation test are shown in Fig. 1. When the injection flow rate was 1 m^3/min during the stimulation tests conducted from August 7 to 8 and from August 10 to 11, no microseismic events were detected. When the injection flow rate was increased to 2~3 m^3/min, the microseismic activity began. The seismic activity increased rapidly when the injection flow rate increased to 4 m^3/min. Similarily, when the injection flow rate was increased from 1 to 2 m^3/min during the circulation test, the seismic activity rate is higher. This result suggests that the rate of microseismic events strongly depends on the injection flow rate. The results obtained in the circulation test are similar to those of the 1992 hydraulic fracturing experiment.

During the circulation test, more than 440 microseismic events were observed of which 330 events were located by the surface network. The largest event had a magnitude of 1.2. The hypocenter distribution of microseismic events obtained is shown in Fig. 2. The seismic cloud distributes along a east-west direction from HDR-1. The hypocenter distribution of microseismic events induced by the circulation test occur over a larger region compared to those that accopmanied the 1992 hydraulic fracturing experiment. The wider sctter during the circulation test is probably due to the longer period of injection that allowed water to more fully permeate the rock. As a reason for this, it can be considered that in the hydraulic fracturing experiment, water of about 2,000 m^3 was rapidly injected into HDR-1 at the maximum injection flow rate of 6 m^3/min to create fractures in a short time, while in the circulation test, water was injected in the ground for many days at a relatively low flow rate of 1 m^3/min ~ 2 m^3/min and as a result the effect of water permeation into the rock was larger than that of the hydraulic fracturing experiment, and it seems that the difference of the injection flow rate resulted in difference in the seismic activity.

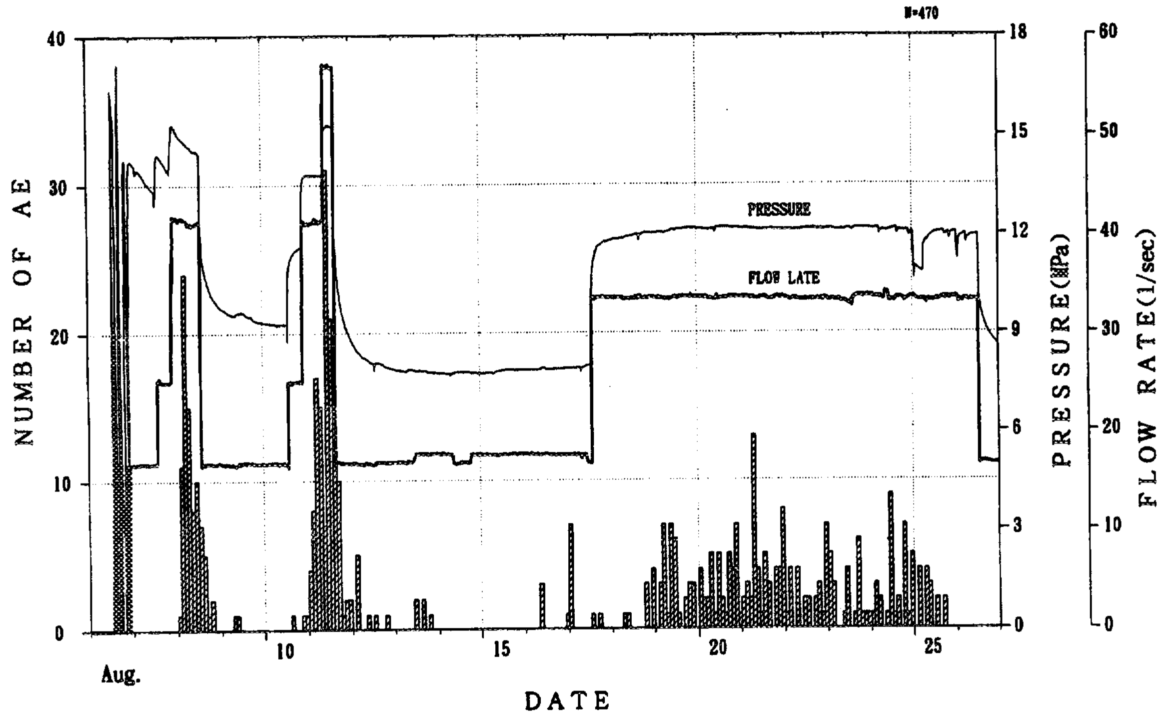


Fig. 1 Wellhead pressure and injection flow rate at HDR-1 during the circulation test and seismic event rate per 2 hours observed at ST-7.

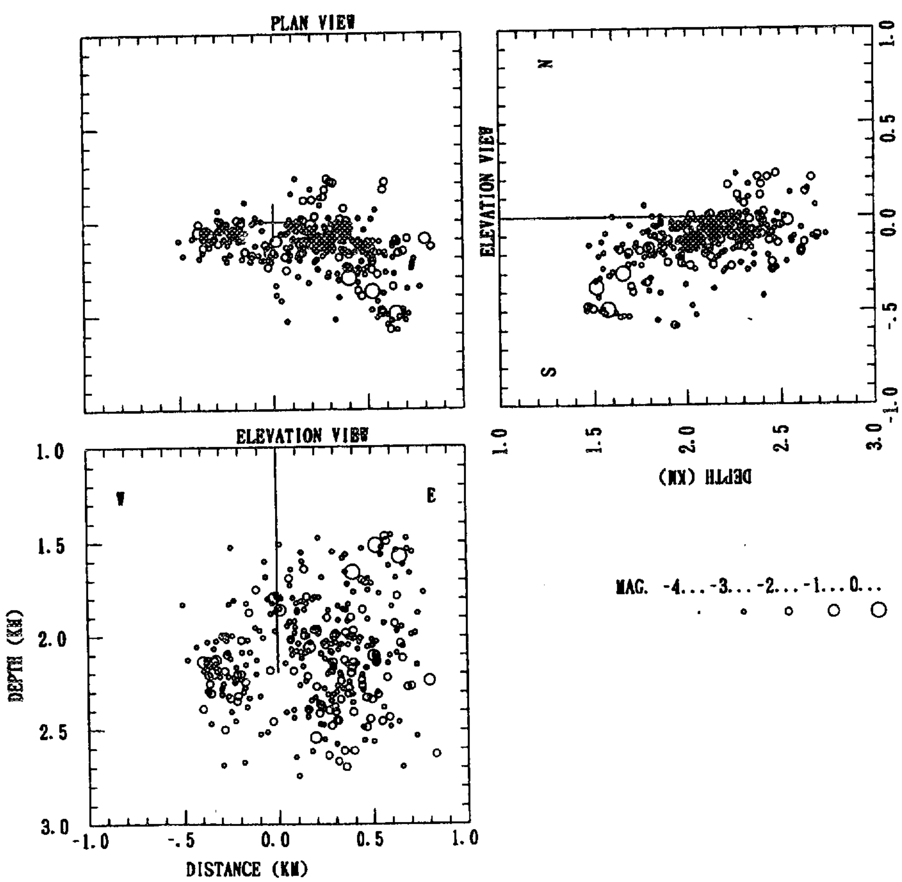
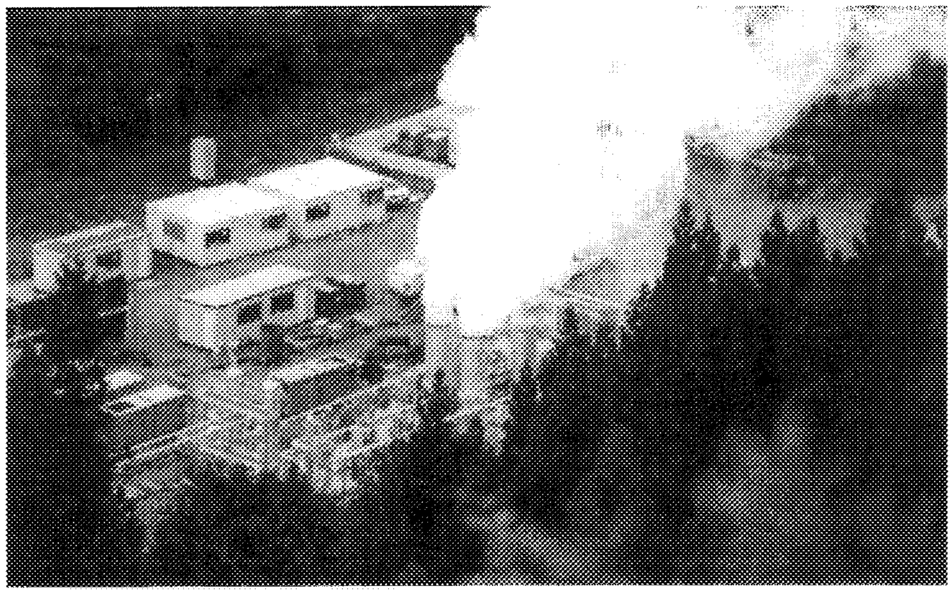


Fig. 2 Hypocenter distribution of microseismic events associated with the circulation test. Upper left : Epicentral distribution. Upper right : Vertical cross section projected onto a north-south plane. Lower left : vertical cross section projected onto an east-west plane. The mark + shows the bottom of HDR-1.

Session 3:
Hijiori II

Session Chair: Andrew Green



A Reexamination of Microseismic Data from the Hijiori HDR Project

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Between 1986 and 1992, a number of hydraulic fracturing and circulation experiments have been carried out at the Hijiori geothermal field in Yamagata prefecture, Japan. Monitoring of microseismic activity has been a key diagnostic technique during these experiments, and a large database of microearthquake locations has been amassed. As part of the MTC project, we apply a recently-developed technique to this data; it uses the location error ellipses as a basis for estimating the underlying causative structures. This allows some insight into the distribution of fractures induced by the hydraulic experiments.

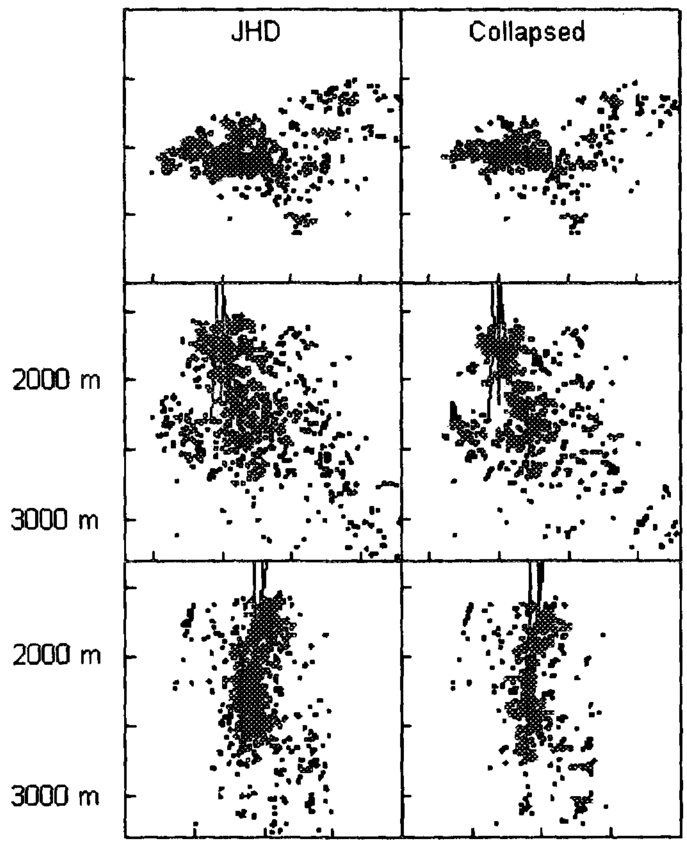

Fig.1 JHD hypocentres (left) and collapsed hypocentres for entire Hijiori data set. The three views shown are, from top to bottom, a plan and sections from the South and the East. Tick marks are at 500 m intervals.

We have applied a joint-hypocentre determination (JHD) relocation and then the collapsing process to almost 750 microseismic events at Hijiori (see Fig. 1). This reveals two zones of seismicity which can be associated with the two reservoirs at Hiojiori, and which we will refer to as fractures. The upper, smaller, one dips to the South at an angle of about 55°. The lower fracture dips to the North and has a dip greater than 80°.

The success of the analysis is best seen when we look at the microseismicity induced during the two stimulations in relation to the injection wells (see Fig. 2). In 1988, the stimulated zone was the bottom 14 m of well SKG-2. The original locations bear little relationship to this zone and are, in general above it. The collapsed hypocentres however, define a fracture that almost exactly intersects the well at the injection point. For the 1992 stimulation, the original locations are again diffuse but are this time generally around the injection interval, the bottom 54 m of well HDR-1. The collapsed hypocentres again define a fracture. This does not intersect the well at the injection point but is displaced about 50 m South of it. It does however start at the same depth as the injection point and extends downwards.

Acknowledgement: The data used in this work was supplied by the New Energy and Industrial Technology Development Organization (NEDO).

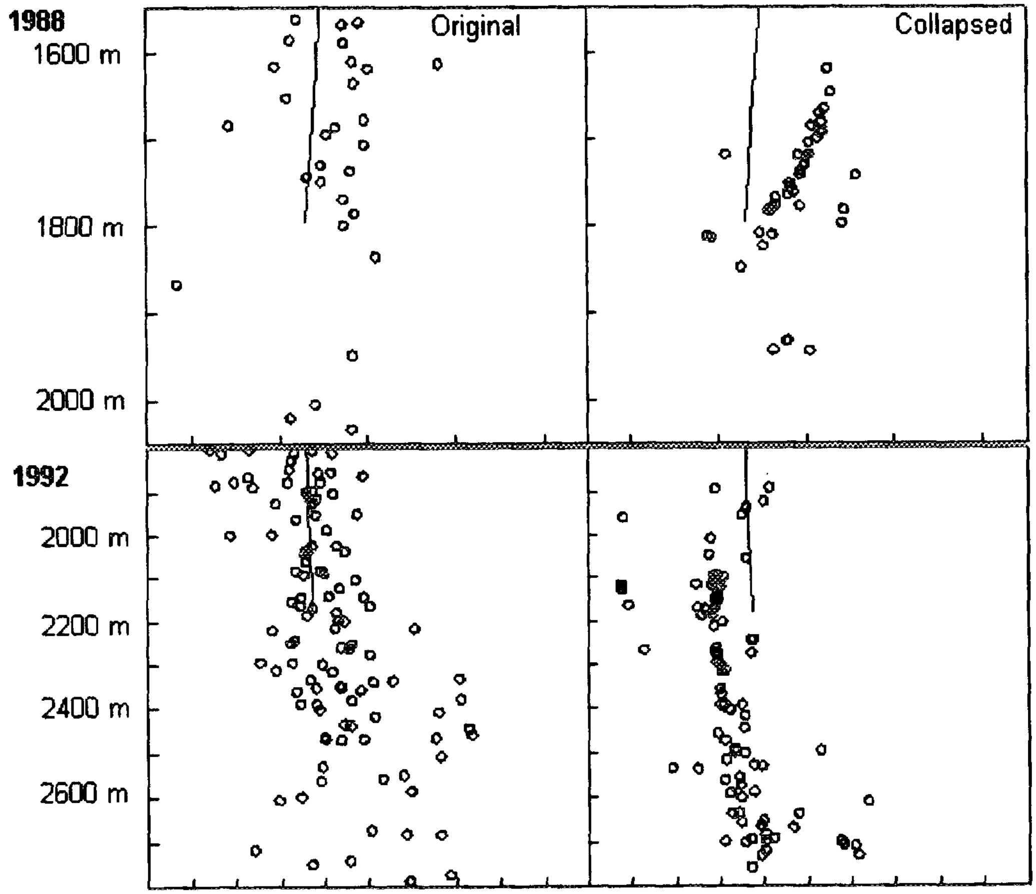

Fig 2. Comparison of original locations and collapsed locations for the two stimulations. The 1988 data (top) is viewed from an azimuth of 75°. The 1992 data (bottom) is viewed from the East. Tick marks are at 100 m intervals.

Characteristic of the Hijiori HDR Reservoir from the Preliminary Circulation Test Results in 1995

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Abstract

As a part of the NEDO project; Development of HDR Power Generation Technology, the Preliminary Circulation Test (PCT) was conducted at the Hijiori HDR test site in 1995. The purpose of the FY 1995 PCT is to understand the characteristic of the Hijiori HDR circulation system and the operating conditions for the future Long Term Circulation Test.

As shown in Figure 1, planed PCT consists of two step-rate tests (on days 1 and 27), two stimulations (on days 3 and 6), and two injection periods at different flowrates (on days 7, 15 and 22). These flow rate changes and stimulations will allow determination of the effects of changes on impedances for characterizing the Hijiori HDR reservoir system. The actual circulation test results are shown in Figures 2 and 3. About 40% of the recovery was obtained from two production wells (HDR-2 and HDR-3) through 25 days of the circulation test shown in Figure 4.

Since the shallow reservoir which intersects HDR-2 and HDR-3 is not isolated from deep reservoir during PCT, fluid flow communication from deep reservoir at HDR-1 to both of deep and shallow reservoirs at HDR-2 and HDR-3 well was observed.

Conclusion & Scope

Through PCT, we could characterize the existing Hijiori HDR deep/shallow circulation system as follows.

a. Injection pressure decreased approximately half after 25 days of PCT.
b. Production flow rate (recovery) didn't change dramatically even the injection rate increased twice (16.7 kg/s to 33.3 kg/s).
c. The effective impedance of HDR-2 was 1.1 Mpa/kg/s, and that of HDR-3 was 2.1 Mpa/kg/s.
d. Circulating fluid temperature at HDR-2 was decreasing while PCT (260°C to 225°C).
e. Circulating fluid temperature at HDR-3 didn't change while PCT (270°C).

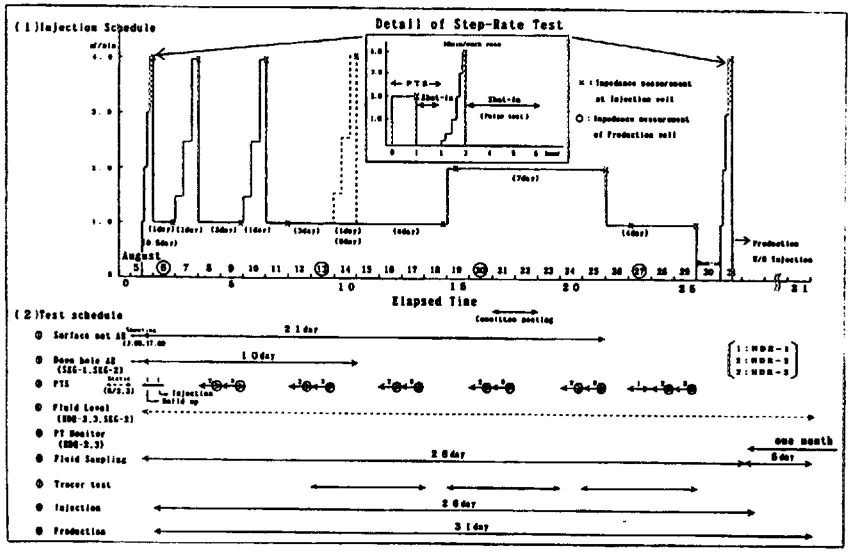

Fig. 1 Planed injection rate for the Preliminary Circulation Test in 1995

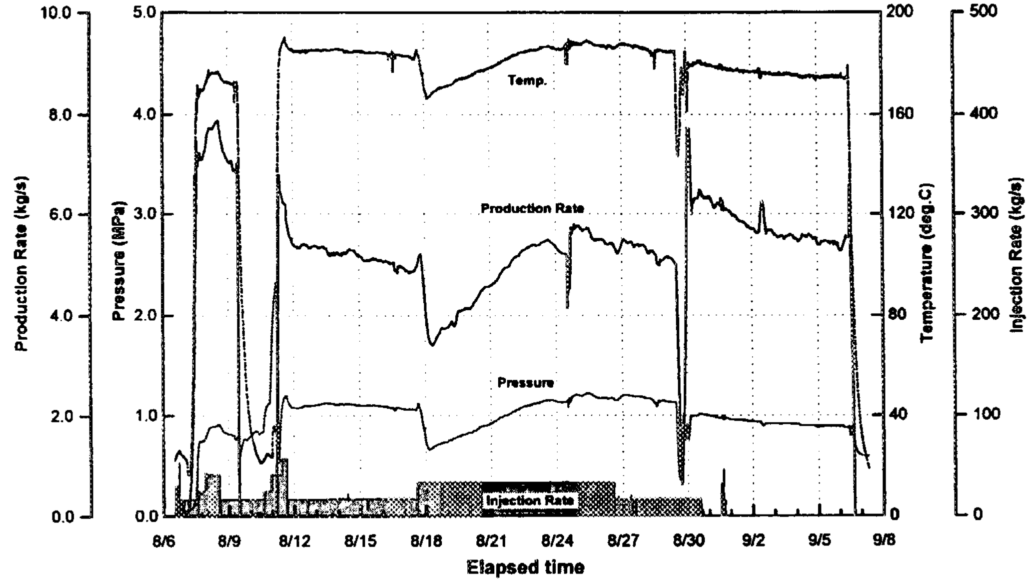

Fig. 2 Production from HDR-2

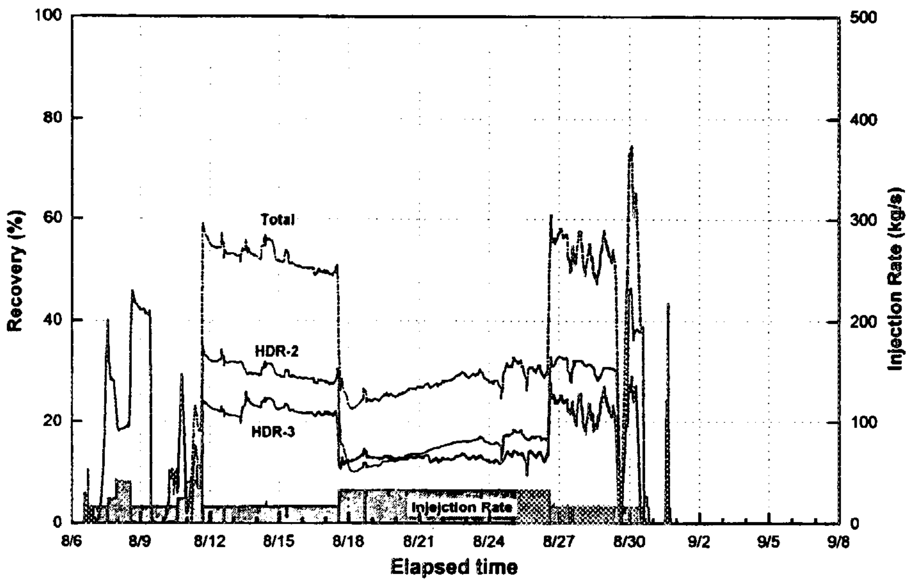

Fig. 4 Recovery efficiency

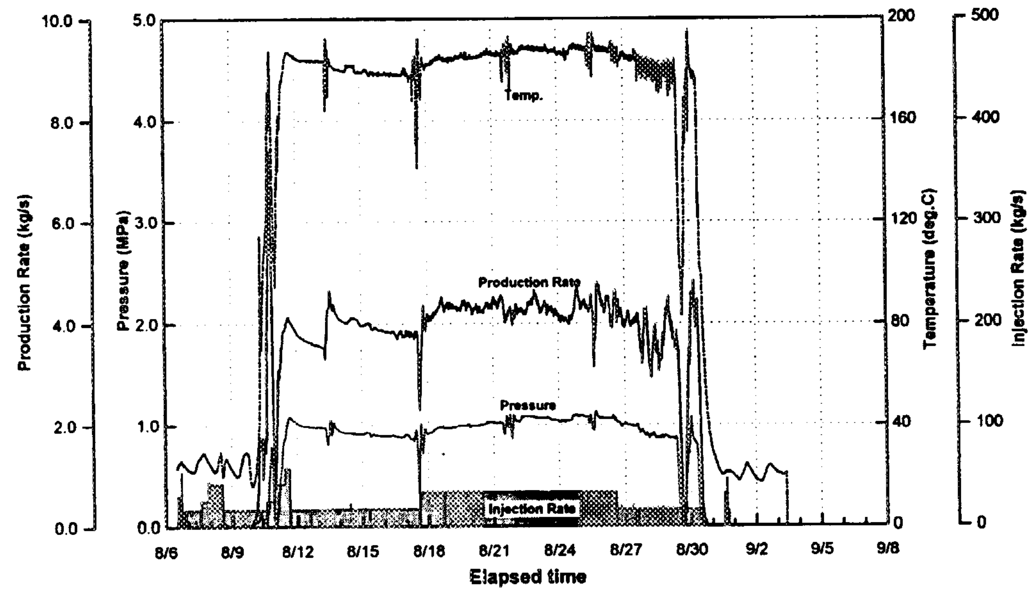

Fig. 3 Production from HDR-3

An HDR System Hydraulics Model and Analysis of the 1995 Preliminary Circulation Test at the Hijiori HDR Site of the NEDO Project, Japan

M. Hyodo, N. Shinohara, and S. Takasugi, Geothermal Energy Research and Development Co.; C.A. Wright and R.A. Conant, Pinnacle Technologies

Abstract

This paper discusses the results of the first fluid circulation in the Hijiori deep reservoir: the 1995 deep reservoir preliminary circulation test. The test revealed that the flow circulation was far more complicated than was originally expected, due to extensive interaction between the deep and shallow reservoirs. The test also increased our understanding of the relationship between the injection pressure and the recovery efficiency, the component impedances of the deep reservoir versus the shallow reservoir, and some unique insights into the operation of multiple production well HDR systems.

The HDR hydraulic analysis model developed for analysis of the Hijiori 1991 shallow reservoir circulation test[1] was expanded and applied to the Hijiori 1995 deep reservoir preliminary circulation tests. The Hijiori deep reservoir HDR setup consists of an injection well (HDR-1) which is cased down to the top of the deep reservoir, and two production wells (HDR-2a and HDR-3), which are cased down to the top of the shallow reservoir, and open hole through the shallow and deep reservoirs.

Figure 1 shows the injection flowrates and pressures during the 1995 test. The analysis of the data from the 1995 deep reservoir test has added to our growing understanding of HDR system engineering, and from this analysis come four major conclusions: (1) there is direct communication between the deep and shallow reservoirs at the Hijiori site; (2) increasing the injection flowrate from 16.7 to 33.3 kg/sec not only reduced incremental recovery efficiency, but actually decreased the total recovery flowrates; (3) a slight impedance bias (and the effect of positive feedback), which initiated production in HDR-2a and blocked production in HDR-3, was overcome by shutting-in HDR-2a, and therefore stimulating HDR-3; and (4) because of the short-circuit between the deep and shallow reservoirs, the component impedances were difficult to measure, so it will be difficult to rigorously optimize the Hijiori deep reservoir HDR system.

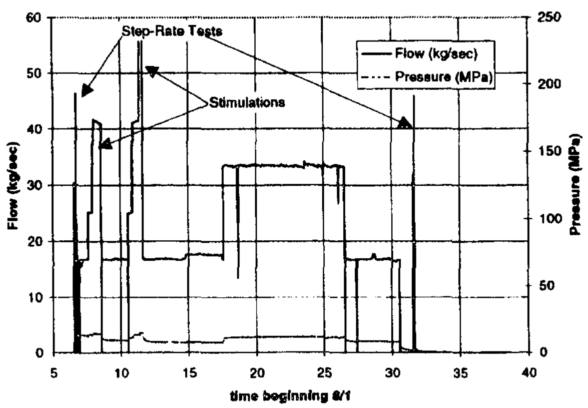

Figure 1. Injection well (HDR-1) Pressure and Flowrate.

Deep/Shallow Reservoir Short-Circuit

As discussed above, there was significant interaction between the deep and shallow reservoirs, as is evident in the production well PTS logs which were run frequently during the circulation tests. Since the injection well is cased through the shallow reservoir, it appears that somehow there is flow DIRECTLY from the deep reservoir at the HDR-1 to the shallow reservoir (the fluid cannot be coming from storage, since the sheer volume of fluid produced from the shallow reservoir is much larger than the stored reservoir fluid volume).

This flow migration could be occurring in the cement annulus around HDR-1, or directly between the deep and shallow reservoirs (the two possibilities are shown graphically in Figure 2). The path of the fluid between the two reservoirs has not yet been determined.

Incremental Recovery Efficiency

Fluid was injected at two steady-state flowrates (16.7 and 33.3 kg/sec), which enabled us to look at the dependence of the recovery efficiency on the injection pressure. The incremental recovery efficiency should be low at very high pressures (because the elevated injection pressure enhances the reservoir conductivity in ALL directions, hence dramatically increasing the loss flow to the far-field), and low at very low pressures (since the reservoir pressure will be insufficient to raise the production wellbore fluid level). There should be some peak incremental recovery efficiency at an intermediate pressure (flowrate). Figure 3 shows the recovery efficiency versus the injection pressure for the Hijiori 1995 deep reservoir preliminary circulation test. We suspect that the optimal recovery efficiency is at some injection rate less than 16.7 kg/sec.

Component Impedances

The total (effective) impedance was divided up into injection wellbore impedance, inlet impedance, reservoir impedance, and outlet impedance. Due to the complexities introduced by the short-circuit between the deep and shallow reservoirs, it was difficult to exactly determine the component impedances. It was, however, determined that the bottom-hole impedances (inlet + reservoir + outlet impedances) in the deep reservoir were 3-5 times more than those for the shallow reservoir. Much of the pressure drop between the injection and production wells was recovered by the large buoyant drive (the difference in hydrostatic head) which was up to 9 MPa during the test.

The outlet friction is an important parameter for HDR system characterization, because it is often a significant part of the total system impedance, and is most likely very pressure dependent, so the outlet impedance might be varied by changing the production back-pressure. The possibility of controlling the impedance by changing production conditions is one very attractive aspect of HDR power development, but this is not possible with the Hijiori 1995 deep reservoir test, since the production wellbores were open to multiple reservoirs.

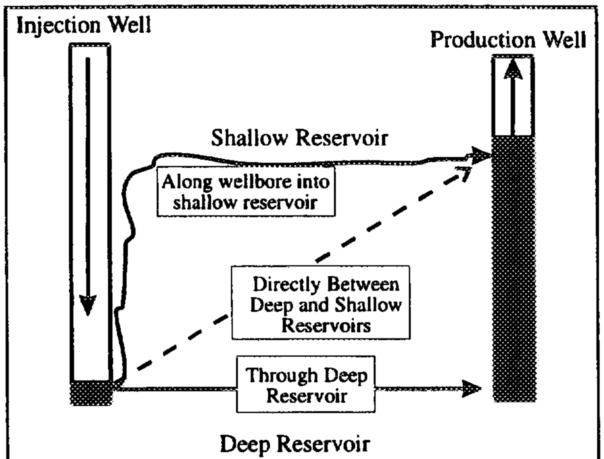

Figure 2. Hijiori 1995 Deep Reservoir Test: Possible Flowpaths (not to scale).

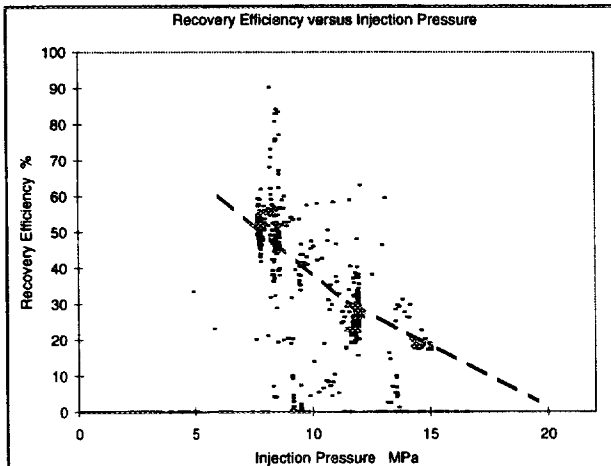

Figure 3. Hijiori 1995 Deep Reservoir Test: Incremental Recovery Efficiency versus Injection Pressure.

Production well balancing

There was a slight preference in flow direction towards HDR-2a, which was reinforced by the reduction of the hydrostatic head in HDR-2a as the cold water in the wellbore was replaced with the hot reservoir fluid. As the hydrostatic head was reduced, the flow preference towards HDR-2a increased. This positive reinforcement kept HDR-3 from producing.

After 3 days of little or no flow from HDR-3 (August 5 - August 8), it was decided that well HDR-2a should be shut-in during the second stimulation in order to reduce the flow bias towards HDR-2a, and to stimulate HDR-3 (by replacing the cold wellbore fluid with hot, produced reservoir fluid and reducing the hydrostatic head). HDR-2a was shut-in during the second stimulation (from August 9 to August 11), which therefore increased the reservoir pressure around HDR-2a, and therefore stimulated production from HDR-3. Interestingly, the surface pressure at HDR-1 did not increase significantly when HDR-2a was shut-in. The pressure at HDR-2a, however, increased almost 1.5 MPa when shut-in. After the second stimulation, the flow from HDR-3 was fairly steady, and HDR-2a was reopened.

[1] Hyodo, M., N. Shinohara, S. Takasugi, C.A. Wright, and R.A. Conant, 1995, An HDR System Hydraulics Model and Detailed Analysis of the 1991 Circulation Test at the Hijiori HDR Site, Japan: Twentieth Stanford Workshop on Geothermal Reservoir Engineering.

Preliminary characterization of the Hijiori HDR deeper system by fluid geochemistry and tracer experiments of a one-month circulation test

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A circulation test was carried out at the Hijiori HDR test site over a one month period in the summer of 1995. Fluid geochemistry was monitored at two production wells, HDR-2 and HDR-3 during the test. Tracer experiments were also conducted three times to characterize the flow in a deep reservoir at a depth of 2200 meters.

Figure 1 shows the changes in the chloride (Cl^-) and sulfate (SO_4^{2-}) concentration in the HDR-2 production fluids. The Cl^- concentration fluctuated over a wide range, from 10 to 2750 ppm during the test. As shown in this figure, the variation of the Cl^- and SO_4^{2-} concentration were closely related to the flow control operation. Changes of fluid geochemistry during the circulation was also affected by the hydraulic interaction between a shallow reservoir at 1800 m depth and the deep reservoir [Tenma et al., 1996]. The Cl^- concentration decreased after a shut-in stage, probably caused by flushing and dilution from the injected water at the bottomhole. A sharp increase of SO_4^{2-} at this stage suggests that anhydrite dissolution was activated when a flow path between the injection wells HDR-1 and HDR-2 was cooled by increasing the flow rate. On the other hand, as shown in Figure

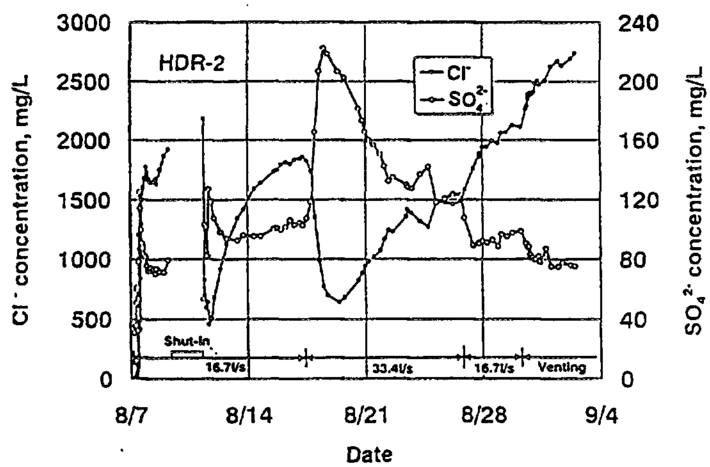

Fig.1. Cl^- and SO_4^{2-} concentration of HDR-2 production fluid

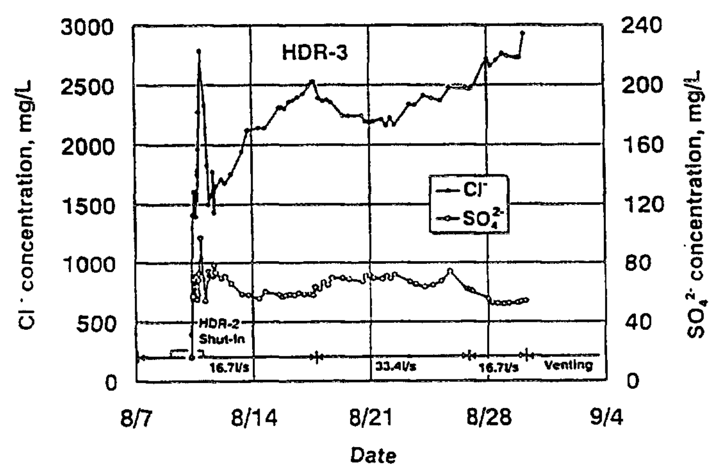

Fig.2. Cl^- and SO_4^{2-} concentration of HDR-3 production fluid

2, the Cl^- and SO_4^{2-} concentrations of the HDR-3 fluids did not fluctuate as much except for a sharp Cl^- peak at the initial stage. The fluid geochemistry of HDR-3 fluids is slightly different from those of HDR-2 in that the Cl^- concentration was higher and the SO_4^{2-} concentration was lower. These differences in the fluid chemistry and also the concentration variations during the test suggest that the connection from HDR-1 to HDR-2 is more dominant than that to HDR-3.

Two or three tracers were used, fluoresceine, Halogens (KI and KBr), and Tungstenate ($Na_2WO_4 \cdot 2H_2O$). A tracer solution of 1 m^3 was injected in to the flow line to HDR-1. Produced fluids were collected at each wellhead by an automatic fluid sampler. The first tracer was injected on August 15 at the flow rate of 16.7 l/s. The second and third experiments were conducted on August 20 and 27, respectively. Figure 3 show breakthrough curves for fluoresceine at the first experiment. These curves strongly suggest the difference in the fracture connections from HDR-1 to HDR-2 and HDR-3. The response of the curves at the three experiments is shifted as shown in Figure 4. This result is due to the transient state of the deep reservoir and also the hydraulic interference at the shallow reservoir during the flow test.

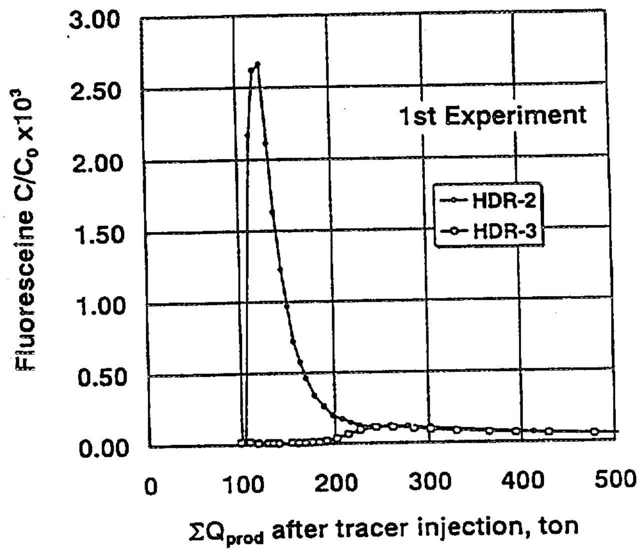

Figure 3. Tracer breakthrough curves at the first experiment. Tracer was injected at 8 a.m. on August 15.

The result of the geochemical monitoring and the tracer experiments reveal the complexity of the flow regime in the multi-well and multi-fracture system at Hijiori.

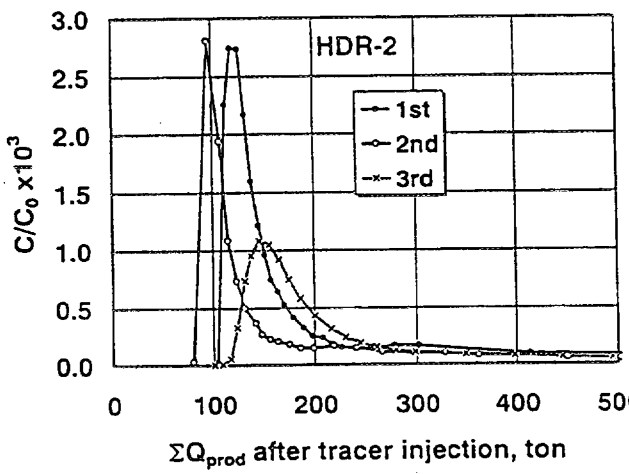

Figure 4. Comparison of response curves obtained from the three experiments

Reference

Tenma, H. et al., Prep. of the 21st Workshop of Geothermal Reserv. Eng., Stanford, 1996.

PRESSURE TRANSIENT ANALYSIS OF INJECTION TEST AT HIJIORI HDR SITE

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Since 1984 Various experiments were done at the HIJIORI HDR test site. The analysis results of the injection test is described below.

The analysis result from 1989 to 1995 is shown in table 1.

We looked for the reservoir parameter (transmissivity, storativity) with comparing the pressure values measured and a pressure change calculated by the one-dimensional axial symmetric reservoir model (the numerical formula).

Example of the comparison between this pressure calculated value and the measurement pressure value is shown in figure 1.

It is possible to estimate that the transmissivity in the HIJIORI area is $1\times10^{-8} m^3/Pa.sec$ from about $1\times10^{-10} m^3/Pa.sec$ from these results and that the storativity is 1×10^{-8} m/Pa from about 1×10^{-10} m/Pa .

FIGURE 1. BUILD UP & FALL OFF PRESSURE_MATCHING RESULT
2nd HDR-1 INJECTION TEST

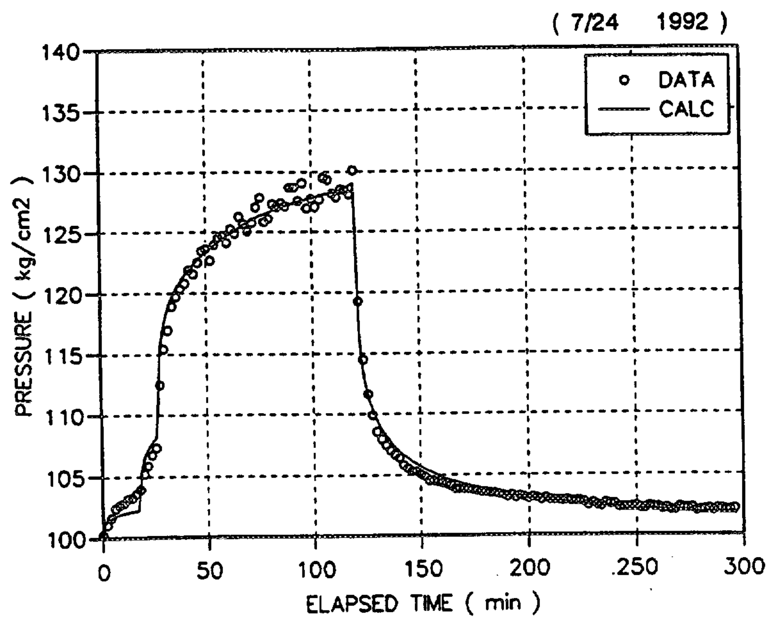

TABLE 1. PRESSURE TRANSIENT ANALYSIS RESULTS 1989 TO 1995 IN HIJIORI HDR TEST SITE

EXPERIMENT DATE		TRANSMISSIVITY $m^3/Pa.sec$	STORATIVITY m/Pa	EXPERIMENT METHOD	ANALYSIS METHOD	OTHERS
1989	10/18	2.97×10^{-9}	1.25×10^{-8}	SKG-2 – HDR-1 interference	pressure matching	shallow reservoir
		1.25×10^{-9}	8.19×10^{-9}	SKG-2 – HDR-2 interference	pressure matching	shallow reservoir
1990	8/3	3.72×10^{-9}	0.967×10^{-8}	SKG-2 – HDR-1 interference	pressure matching	shallow reservoir
		3.67×10^{-9}	1.12×10^{-8}	SKG-2 – HDR-2 interference	pressure matching	shallow reservoir
	10/27~28	1.42×10^{-9}	5.58×10^{-8}	SKG-2 – HDR-1 interference	pressure matching	shallow reservoir
		1.60×10^{-9}	2.10×10^{-8}	SKG-2 – HDR-2 interference	pressure matching	shallow reservoir
		1.35×10^{-9}	3.44×10^{-8}	SKG-2 – HDR-3 interference	pressure matching	shallow reservoir
1992	7/19	5.61×10^{-16} ~ 1.86×10^{-11}	3.01×10^{-17} ~ 4.45×10^{-16}	HDR-1 build up & fall off	pressure matching	HDR-1 before fracturing deep reservoir
	7/24	6.76×10^{-10}	1.09×10^{-10}	HDR-1 build up & fall off	pressure matching	HDR-1 after fracturing deep reservoir
	8/7	3.89×10^{-9}	1.82×10^{-9}	HDR-1 build up	pressure matching	HDR-1 after plug back deep & shallow reservoir ?
1993	8/30~31	1.97×10^{-9}	3.98×10^{-9}	HDR-1 – HDR-3 interference	pressure matching	deep & shallow reservoir ?
	8/31	9.82×10^{-10} ~ 1.16×10^{-9}	1.02×10^{-9} ~ 2.91×10^{-8}	HDR-1 build up	pressure matching	deep & shallow reservoir ?
	8/31	2.14×10^{-10}		HDR-1 fall off	horner plot	deep & shallow reservoir ?
	9/2	1.23×10^{-9}		HDR-3 fall off	horner plot	deep & shallow reservoir ?
1994	9/22	1.66×10^{-8}	6.74×10^{-9}	HDR-1 – SKG-2 interference	pressure matching	deep & shallow reservoir
		9.44×10^{-9}	6.58×10^{-9}	HDR-1 – SKG-2 interference	pressure matching	deep & shallow reservoir
		8.21×10^{-9}	4.21×10^{-9}	HDR-1 – HDR-2 interference	pressure matching	deep & shallow reservoir
		6.17×10^{-9}	6.75×10^{-8}	HDR-1 – HDR-3 interference	pressure matching	deep & shallow reservoir
	9/23	1.48×10^{-10} ~ 5.41×10^{-10}	2.60×10^{-10} ~ 6.60×10^{-8}	HDR-1 build up	pressure matching	deep & shallow reservoir
1995	8/6	4.9×10^{-10} ~ 2.4×10^{-9}	1.6×10^{-10} ~ 1.4×10^{-9}	HDR-1 build up	pressure matching	deep reservoir before circulation
	8/31	3.5×10^{-9}	1.2×10^{-9}	HDR-1 build up	pressure matching	deep reservoir after circulation

ENERGY EXTRACTION ANALYSIS OF THE
1995 HIJIORI 25-DAY CIRCULATION TEST

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A 25-day circulation test was carried out in the summer of 1995 to characterize the deeper reservoir of the Hijiori HDR resource. A description of the test, which included stimulation of the injection well at the start and conclusion of the test period, is given in NEDO (1996). The test data showed production flow in the two production wells from both the deeper reservoir at 2200 m and the original upper reservoir at 1800 m. Analysis of the test data for the two production wells were treated as independent zonal sectors, as described by Kruger and Yamaguchi (1993) for the Hijiori 90-day circulation test of the upper reservoir and Kruger and Yamamoto (1995) for the Ogachi 151-day circulation test. The method provides an estimation of the thermal energy extracted from the two reservoir zonal sectors during the 25 days of circulation.

From the surface and downhole measurements of the test provided by NEDO (1996), an upper limit to the reservoir volume (and corresponding useful heat content) was estimated based on the heat transfer flow geometry for the zonal sectors. The flow angles were calculated from the fractional recovery in each well relative to the injection flowrate. The reservoir volume of each of the two zonal sectors is given as

$$V = (\alpha/360)\pi R^2(Z_b + 2/3(Z_a + Z_c))$$

where R = lateral distance from injection to production well
Z_b = planar thickness from injection well open interval
Z_a = conic thickness above injection well open interval
Z_c = conic thickness below injection well open interval.

For the values given by NEDO (1996), the resulting sector volumes are:

$V(HDR\text{-}2) = 2.25\times10^6\,m^3$ and $V(HDR\text{-}3) = 4.05\times10^6\,m^3$.

The heat content of each zonal sector is given by

$$HC = (\rho V)\, C_p\, (T_o - T_a)$$

where ρ = rock density (kg/m^3)
V = reservoir flow volume (m^3)
C_p = rock specific heat (J/kg-C)
T_o = mean initial reservoir temperature (C)
T_a = application abandonment temperature (C).

For the given Hijiori rock thermal properties and an abandonment temperature of 140 °C for generation of electricity, the respective heat contents are:

HC(HDR-2) = 0.79 PJ and HC(HDR-3) = 1.42 PJ.

The heat extracted was calculated by spreadsheet integration over constant flowrate periods in fractional hours on a daily basis. The data for well HDR-3 is illustrated in Table 1. The respective heat extracted from the two wells were HE(HDR-2) = 10.8 TJ and HE(HDR-3) = 5.8 TJ. The respective fractions produced were FP(HDR-2) = 1.4 % and FP(HDR-3) = 0.41 %.

Table 1. HDR-3 Zonal Sector Heat Extraction

Date Aug	Time	Δt (hr)	Q(p) (kg/s)	T(bh) (C)	H (kJ/kg)	ΔH (kJ/kg)	ΔHE (GJ)	ΣHE (TJ)
10	12:00	0.00	0.000	246	1066	0	0.0	0.00
10	14:00	2.00	1.804	246	1066	919	11.9	0.01
10	22:00	8.00	2.536	246	1066	919	67.1	0.08
10	23:00	1:00	2.536	246	1066	919	8.4	0.09
11	03:00	0:00	0.000	246	1066	919	0.0	0.09
11	10:00	7:00	3.678	246	1066	919	85.2	0.17
11	16:00	6:00	4.154	246	1066	919	82.5	0.26
12	00:00	8:00	3.890	246	1066	919	103.0	0.36
13	00:00	24:00	3.577	246	1066	878	271.3	0.63
14	00:00	24:00	4.268	246	1066	878	323.8	0.95
15	00:00	24:00	3.438	247	1071	883	262.3	1.22
16	00:00	24:00	4.016	247	1071	883	306.4	1.52
17	00:00	24:00	3.204	247	1071	883	244.4	1.77
17	14:00	14:00	1.452	247	1071	883	64.6	1.83
18	00:00	10:00	2.928	247	1071	883	93.1	1.92
19	00:00	24:00	3.930	247	1071	903	306.6	2.23
20	00:00	24:00	3.443	247	1071	903	268.6	2.50
21	00:00	24:00	6.430	247	1071	903	501.7	3.00
22	00:00	24:00	4.855	247	1071	903	378.8	3.38
23	00:00	24:00	4.440	248	1076	908	348.3	3.73
24	00:00	24:00	3.662	248	1076	908	287.3	4.02
25	00:00	24:00	4.560	248	1076	908	357.7	4.37
26	00:00	24:00	3.640	248	1076	908	285.6	4.66
26	14:00	14:00	3.199	248	1076	908	146.4	4.80
27	00:00	10:00	3.544	249	1081	913	116.5	4.92
28	00:00	24:00	2.554	249	1081	893	197.1	5.12
29	00:00	24:00	2.633	249	1081	893	203.1	5.32
29	23:00	23:00	4.736	249	1081	893	350.2	5.67
30	00:00	1:00	4.500	249	1081	893	14.5	5.69
30	08:00	8:00	4.500	249	1081	893	115.7	5.80
30	10:30	0.00	0.000	249	1081	893	0.0	5.80

The data show a mean flowrate of 3.80 kg/s, mean enthalpy increase of 901 kJ/kg, mean heat extraction rate of 3.43 kJ/s for the total heat extracted of 5.8 TJ. The results for this short circulation test indicate that the two zonal sectors, with frequent flowrate changes and shutin periods, probably did not attain steady-flow heat-extraction conditions in the extended reservoir. Never-the-less, the small fractions produced for the assumed zonal sector volumes, suggest potential circulation lifetimes for cooldown to the abandonment temperature in the range of 5 to 15 years for this experimental facility. A long-term circulation test of at least one year at constant flowrate is necessary to characterize the heat extraction capability of the deeper Hijiori reservoir.

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Session 4:
Fenton Hill

Session Chair: Yoshiteru Sato

Overview of the Fenton Hill HDR Project

David Duchane and James N. Albright,* Los Alamos National Laboratory

In 1970, researchers from the Los Alamos National Laboratory filed for a US Patent on a process employing hydraulic fracturing to extract heat from a dry geothermal reservoir. The concepts outlined in that patent application formed the basis for the United States Hot Dry Rock (HDR) Geothermal Energy Development Program formally initiated in 1974, and for all subsequent work on the extraction of energy from HDR. Since its inception, US HDR work has been sponsored primarily by the US DOE and its predecessor agencies, with smaller amounts of funding from the National Science Foundation and the California Energy Commission. Domestic HDR research and development work has been conducted principally under the direction of the Los Alamos National Laboratory, with essentially all field experiments carried out at the HDR test site at Fenton Hill in the Jemez Mountains of northern New Mexico. Under an International Energy Agreement, Japan and Germany participated in the development of the HDR concept at Fenton Hill from 1980 to 1986, contributing both financing and technical personnel to the HDR project.

The development of the world's first HDR circulation system began in earnest at Fenton Hill in 1974. A small reservoir was created by hydraulic fracturing in granitic rock at a depth of about 3000 m and a temperature of 185°C. This reservoir, together with the two wellbores penetrating it, formed the Phase I system. The Phase I system was evaluated in a series of flow experiments between 1978-1980. These tests demonstrated the scientific feasibility of extracting heat from engineered geothermal reservoirs.

In 1980, work was begun on a much larger, deeper, and hotter Phase II reservoir. It was not until 1986, that the Phase II system was completed and initially flow tested. Since that time, the Phase II reservoir has been subjected to extensive evaluation under both static and flow conditions. Centered at a depth of about 3500 m in rock at a temperature of 220-240°C, the Phase II reservoir is believed to have a flow-connected volume of 5-20 million cubic meters (on the order of 50 to 200 times the volume of the Phase I reservoir) based on seismic and hydraulic measurements.

Between 1987 and 1992, a permanent surface plant was constructed at Fenton Hill and connected to the Phase II wellbores. The complete Phase II system today consists of a highly automated, closed-loop in which the same water can be continuously recirculated. Thermal energy is absorbed from the hot rock during each pass through the reservoir and then rejected via an air-cooled heat exchanger at the surface. A high pressure injection pump provides the sole motive force for the operation.

A long-term flow test (LTFT) of the Phase II HDR system was conducted during 1992-1993. Steady state operations during the LTFT typically involved injection at a pressure of about 27.3 MPa believed, on the basis of measurements of reservoir seismicity, to be the highest pressure that could be maintained without causing an increase in reservoir volume. A backpressure of 9.7 MPa was typically held on the production wellhead, although the injection pressure was high enough so that the water could be returned to the surface at backpressures as high 15.0 MPa without large reductions in production rate. A very limited amount of testing during this period involved operation under cyclic conditions during which the injection and production parameters were intentionally

* Presenter

varied to demonstrate that the output of the reservoir could be rapidly adjusted to meet changing demands for power.

The LTFT was highly successful in demonstrating that the Phase II Fenton Hill system could be operated routinely to produce significant amounts of energy. During a total of about 9 months of steady-state circulation approximately 80 billion BTUs of thermal energy were extracted from the Phase II reservoir with no decline observed in the temperature of the fluid produced at the surface.

The LTFT provided solid evidence that water loss need not be a serious problem in the operation of HDR reservoirs. Water consumption declined continuously as a function of the time, as the system was held at a constant operating pressure, reaching a level of only 7% of the injected volume on a trend line that indicated an eventual decline to 2-3% or even less. Dissolved solids remained at low levels and the circulating fluid picked up essentially no suspended solids. Because the HDR plant was fully-automated, all the flow testing was conducted with a minimum of manpower. The site was typically unmanned at night.

With encouraging flow test results in hand, the DOE issued a solicitation in December 1994 seeking an industrial partner to develop a facility to produce and market energy from an HDR resource. Bids were received from several organizations. In late June 1995, a technical review committee appointed by the DOE selected a winning bidder and recommended that the project go forward.

In the spring of 1995, a reservoir verification flow test (RVFT) was initiated to show that the Phase II system was still viable after two years of standby, during which the pressure on the reservoir had been allowed to drop significantly below the level employed during routine circulation. The operating conditions and production levels that had prevailed during the LTFT were re-established within a few weeks, clearly demonstrating the long-term resiliency of the Fenton Hill HDR reservoir. Another 20 million BTUs of energy were extracted from the reservoir during about 2 months of testing.

After several weeks of operation under steady-state conditions, a cyclic operating schedule was implemented to investigate the capability of the Fenton Hill reservoir to rapidly adapt to changes in power demand similar to those encountered by electric power companies on a daily basis. The cyclic testing demonstrated that energy production could be increased by about 60% from a baseline level within a period of only 2-3 minutes, held at that elevated level for 4 hours, and then rapidly reduced for the remainder of a 24-hour repetitive production cycle. Obviously, many other cyclic production schedules might be employed in the operation of an HDR facility to obtain the maximum economic return, but limited project resources did not permit further evaluation of this energy production strategy.

In October 1995, confronted by a tightening federal budget and low predicted future energy prices, the DOE canceled the solicitation for an industry-led project to produce and market power from an HDR resource. Because of the potential for HDR demonstrated by the Fenton Hill flow testing during the period 1992-1995 and the continued high level of industrial interest, the DOE decided to restructure the national HDR program to emphasize further research and development, but not commercialization.

In announcing the restructuring of the HDR Program, the USDOE also issued a directive to decommission the Fenton Hill facility. Work to shut down all geothermal activities at the site is now well underway. All the wellbores will be plugged and abandoned and the surface plant will be dismantled. Physical assets at the site will be transferred to other groups at the Los Alamos National Laboratory that can make use of the site. With the termination of operations, Fenton Hill, the world's first, largest, and hottest HDR reservoir, will pass into history. A new direction in HDR work in the US will begin as a restructured HDR Program is formulated, but, as of today, the outline of that future course has yet to be firmly established.

The other papers presented in this Forum session will provide details of the experimental work of the last several years at Fenton Hill and the pertinence of these finding to the eventual implementation of HDR as a reliable energy technology for the world of the 21st century.

1995 Reservoir Flow Testing at Fenton Hill, New Mexico

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Renewed flow testing of the HDR reservoir at Fenton Hill began on May 10, 1995 after a 2-year hiatus following the end of long-term flow testing in May 1993. This third major phase of full-power flow testing of the Phase II reservoir lasted just over 9 weeks, until July 14, 1995.

There were three principal segments to this renewed period of flow testing: An initial 5 weeks of reservoir circulation at a backpressure of 9.65 MPa (1400 psi) to reestablish the steady-state operating conditions that existed at the end of the Second Phase of the Long-Term Flow Test (LTFT) in April 1993, several weeks of operation at a higher production backpressure of 15.2 MPa (2200 psi) and, finally, six days of cyclic flow operation at the same nominal backpressure of 15.2 MPa, with daily 4-hour surges of production flow accomplished by a programmed reduction in the backpressure to a final value close to 3.4 MPa (490 psi). (This last test is covered in a companion paper in this HDR Forum.) One of the primary objectives in reestablishing the initial steady-state operating conditions was to determine whether a change in the character of the reservoir flow observed in May 1993, which apparently resulted from a sudden redistribution of flow paths in the interior of the reservoir during a 3-day cyclic flow experiment, would persist given the thermal recovery within the reservoir region in the intervening 2 years.

The rate of water loss from the boundaries of the reservoir during the 1995 flow testing indicates that we had "reset" the ambient far-field pressure level which controls the diffusional loss of fluid. In 1992, the LTFT was begun after a multi-year period of reservoir pressurization at 15 MPa (2180 psi), while the 1995 flow testing was initiated after many months of reservoir pressure maintenance at 10 MPa (1450 psi). At equivalent times following the initiation of circulation in 1992 and 1995 (after 5 weeks of circulation in each case), and under similar reservoir operating conditions, the water loss rates were 0.88 l/s (14 gpm) and 1.07 l/s (17 gpm), respectively. primarily reflecting the difference in the ambient far-field pressure levels during these two tests.

FLOW TESTING AT A BACKPRESSURE OF 9.65 MPa (1400 PSI)

For the first 5 weeks of flow testing, the reservoir was operated in pressure control with an injection pressure of 27.3 MPa (3960 psi) and a production backpressure of 9.65 MPa (1400 psi), the same operating pressures that existed near the end of the second phase of the LTFT in April 1993 (Brown, 1994). It should be noted that 5 weeks were required to establish steady-state reservoir operating conditions because the reservoir was initially at a fairly low pressure of 10.8 MPa (1570 psi).

After a 2-year hiatus in testing, it was found that the reservoir flow behavior was intermediate between that measured near the end of the LTFT in April 1993, and that measured after the spontaneous flow increase that occurred in May 1993 during the cyclic flow experiment (Brown, 1994). This would suggest that thermal recovery within the reservoir region during the intervening 2 years nullified about two-thirds of the sudden reduction in reservoir flow impedance. This assertion is supported by tracer studies that indicate a flow distribution within the reservoir during 1995 flow testing intermediate between that existing near the beginning of the First Phase of the LTFT in May 1992 and that existing near the end of the Second Phase of the LTFT in April 1993.

Table I compares reservoir performance near the end of Phase 1 testing in 1995 to the measured performance **(1)** at the end of the Second Phase of the LTFT in April 1993 and, **(2)** after the sudden drop in flow impedance that occurred in May 1993 (Brown, 1993).

Table I

Comparison of Reservoir Flow Performance at a Backpressure of 9.65 MPa Between 1995 and Two Times in 1993 Near the End of the LTFT

		(1)	**(2)**
Dates Measured:	May 11 1995	April 12-15 1993	May 13 1993
Injection Conditions:			
Flow Rate, l/s	8.0	6.5	8.2
Pressure, MPa	27.3	27.3	26.6
Production Conditions:			
Flow Rate, l/s	6.6	5.7	7.7
Backpressure, MPa	9.65	9.65	9.65
Temperature, °C	185	184	190

As shown, the 1995 production flow of 6.6 l/s is intermediate between that existing just prior to the end of the LTFT on April 12-15, 1993 (5.7 l/s) and that following the sudden increase in the production flow on May 6, 1993 (7.7 l/s). From these flow data, it appears that the 1995 reservoir flow impedance was about halfway between the levels existing directly before and after the sudden drop in impedance in May 1993. It is suggested that the thermal recovery of the reservoir during the intervening 2 years may account for this observed impedance behavior.

FLOW TESTING AT A BACKPRESSURE OF 15.2 MPa (2200 PSI)

When steady-state reservoir operating conditions were finally reestablished after 5 weeks of circulation, the production backpressure was increased to 15.2 MPa (2200 psi) on June 14, 1995. This change in backpressure produced a further pressure dilation of the joint network in the vicinity of the production well, rapidly increasing the storage capacity of the reservoir in this region and briefly decreasing the production flow rate. The reservoir pressure distribution required about 8 days to stabilize after this perturbation, with the net production flow rate finally reaching a steady-state level of 6.2 l/s, compared to a 6.6 l/s rate previously observed at a backpressure of 9.65 MPa.

Table II provides a comparison of two 15.2-MPa backpressure operating points; the first measured after 14 days of circulation at this higher backpressure during 1995, and the second measured in December 1992. The most significant difference between these two steady-state tests is the 17% higher production flow rate observed during 1995 testing. This increase in flow undoubtedly resulted from the change in the reservoir impedance in May 1993 as discussed above. It is almost the same as the 16% increase in the 1995 production flow rate at a backpressure of 9.65 MPa, when compared to the corresponding production flow rate in April 1993 (see Table I).

Table II

Comparison of Present Reservoir Performance at a Backpressure of 15.2 MPa (2200 psi) to That Determined Between the Two Phases of the LTFT in 1992

	June 27-29, 1995	Dec. 10, 1992
Injection Conditions:		
Flow Rate, l/s	7.84	7.33
Pressure, MPa	27.3	27.3
Production Conditions:		
Flow Rate, l/s	6.25	5.45
Backpressure, MPa	15.2	15.2
Temperature, °C	183	177
Water Loss Rate, l/s	1.17	1.10

Temperature logs of the production well were conducted on June 22 and July 12, 1995 to determine the change in the mixed-mean reservoir outlet temperature at a depth of 3280 m. Although the picture is somewhat confused by thermal convection within the reservoir region during the 2-year hiatus in flow testing, these data, as listed in Table III, suggest that there has been an overall cooling of the reservoir by about 2°C during the course of Phase II reservoir flow testing.

Table III

Reservoir Production Temperature at a Depth of 3280 m

Date of Log:	7/16/92	3/16/93	6/22/95	7/12/95
Fluid Temperature, °C	228.2	227.8	227.3	226.4

Natural convection within the pressure-dilated reservoir region during the 2-year shut-in period would have tended to drive the reservoir region toward a more isothermal temperature distribution. Perhaps this same phenomenon also led to the apparent slight decrease of about 2°C in the mixed-mean production fluid temperature at the reservoir outlet.

CONCLUSIONS

Flow testing of the Fenton Hill HDR reservoir during 1995 has demonstrated that engineered geothermal systems can be shut-in for extended periods of time with apparently no adverse effects.

As a result of the sudden flow impedance reduction that led to an almost 50% increase in production flow near the end of the Second Phase of the LTFT in May 1993, we were uncertain as to the state of the reservoir after being shut-in for 2 years. The flow performance observed during 1995 flow testing was found to be intermediate between that at the end of the Second Phase of the LTFT and that following the subsequent sudden flow increase in May 1993. This would imply that whatever caused the sudden reduction in impedance in the first place is somehow associated with the cooldown of the reservoir near the injection interval, since temperature recovery at the surfaces of the surrounding open joints is the most obvious phenomenon expected to occur during a prolonged shut-in of the reservoir.

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Reactive and Non Reactive Tracers in Geothermal Systems: The Fenton Hill, New Mexico Hot Dry Rock Site.

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ABSTRACT

This paper reviews the tracer test data collected during the 1995 flow test of the Hot Dry Rock (HDR) reservoir at Fenton Hill, NM. The use of both reactive and non reactive tracer compounds in geothermal reservoirs is discussed, specifically concerning the two tracer tests conducted during the summer of 1995. In the HDR reservoir, tracer tests have been used frequently to measure the change in flow volume over a period of time. This report describes how tracer technology offers an excellent means to measure flow volume in systems where injection is part of the method of operation.

INTRODUCTION

The goal of the 1995 flow test was to demonstrate that heat can be extracted from the Hot Dry Rock reservoir under various production conditions without causing a decrease in production fluid temperature (Brown, 1996); this experiment is referred to as the Reservoir Verification Flow Test (RVFT). One way to study potential temperature drawdown involves the injection of chemical tracers into the reservoir. Traditionally, non reactive tracers measure the residence time of fluid within a reservoir, whereas reactive tracers can be used to simulate transport of particular solutes. In the Hot Dry Rock reservoir, p-toluene sulfonic acid (p-TSA) was used as the non reactive tracer compound, and sodium fluorescein (NaFl) was used due to its relative ease of field analysis, but is also considered to be a reactive compound.

Table 1: Results of tracer tests of the HDR reservoir at Fenton Hill, NM.

	Modal volume (m^3)	Dispersion volume (m^3)	Integral mean volume (m^3)	First arrival volume (m^3)
Date of test	p-TSA*	p-TSA	p-TSA	p-TSA
6/06/95	389	610	1789	88
7/11/95	357	743	1630	111

RESULTS AND DISCUSSION

The residence time density of a solute (i.e., tracer) is defined as the fraction of produced fluid that had a specific residence time in the reservoir (Robinson and Tester, 1984). *Figure 1* is a plot of the two tracer distribution curves produced during the RVFT of 1995. As heat is extracted from the reservoir, the average fracture aperture increases. This may lead to a wider distribution of flow throughout the reservoir, or the flow may channel into the main flow paths. *Table 1* shows that there was little change in reservoir volume between the two tests. However, there was more spread in the tracer response for the second test. Load-following experiments were conducted in the time between tracer tests (Brown, 1996), and it is possible that this may have influenced reservoir flow patterns. *Figure 2* shows the cumulative tracer responses for the two experiments. Recovery for fluorescein was much less in each test than for p-TSA due to the reactive nature of fluorescein (Adams and Davis, 1991; Callahan, 1996). However, the differences in fluorescein recovery for the two experiments may be interpreted in a semi-quantitative way. Because less fluorescein was recovered in the July test, it may be inferred that reservoir conditions caused a higher fraction of the chemical to react either thermally (higher reservoir temperatures) and/or chemically (lower fluid pH). The former condition seems more likely than the latter, because there were no measured changes in fluid chemistry during the duration of the RVFT. Regardless, the flow was more disperse during the July, 1995 tracer test than in June.

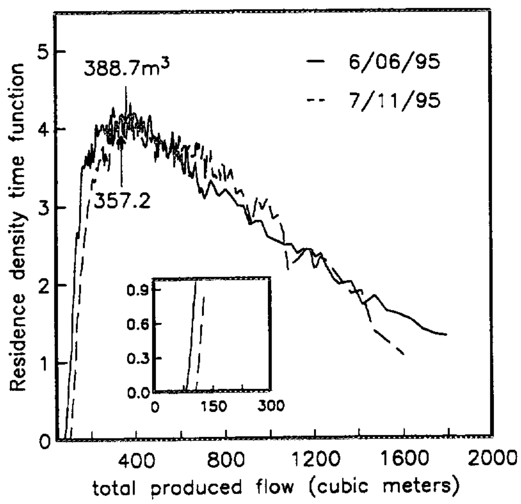

Fig. 1. Tracer test results, p-TSA, 1995.

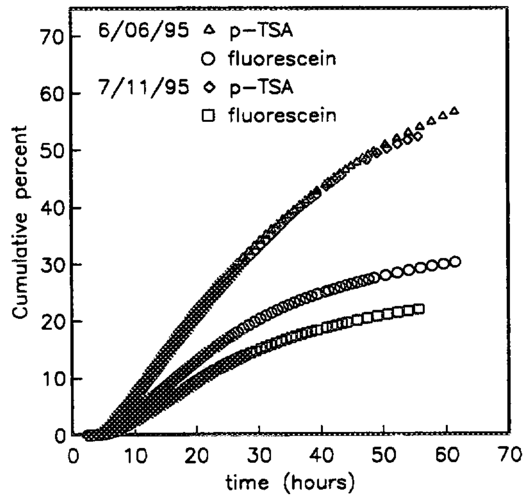

Fig. 2. Cumulative tracer recovered, 1995 tests.

CONCLUSIONS

1. During the RVFT, two tracer tests were conducted at the Hot Dry Rock reservoir at Fenton Hill, NM. Modal and integral mean volumes remained relatively constant between June and July, 1995. It is assumed that continuous production and the load-following experiments did not change the total flow-through volume of the reservoir in this time. Also, from the June test, it is apparent that there was no evidence of flow channeling after a two-year hiatus at Fenton Hill. Furthermore, the data collected from these tracer tests proves that tracer technology is an efficient, inexpensive way to accurately measure the flow volume in HDR reservoirs.

2. Dispersion in the reservoir increased during a span of one month. This was caused by either an increase in fracture apertures due to heat extraction, or by opening "new" fractures through continuous production. Each occurrence would result in an increase in dispersion; however, the former explanation would rely on increased dispersion within individual fractures, whereas the latter hypothesis involves a more broad distribution of fracture apertures. Because the integral mean volume did not change substantially, it seems unlikely that more fractures contrib-

contributed to flow later in the RVFT. The volume of the established flow paths would have to decrease to counter the opening of new fractures, which is unlikely to happen as heat is extracted from the reservoir. However, it is possible that the state of stress in the reservoir is at an angle oblique to the fractures, thus allowing an increase in fracture surface area over time while maintaining a relatively constant flow volume. Mathematical and computer models which include heat extraction (e.g., GEOCRACK) may help in addressing this hypothesis.

3. Fluorescein behaves as a reactive tracer in the Fenton Hill reservoir, most likely due to the high temperatures at depth, the slightly acidic nature of the reservoir fluid and the possible sorption on rock surfaces. Therefore, fluorescein may be used in a qualitative way to measure temperature trends in certain geothermal reservoirs.

FUTURE WORK

Investigations on fracture-flow dispersion are being conducted using finite element computer modeling. The main focus of these studies is to identify the main controls on dispersion within a geothermal reservoir. The purpose is to create a computer model that can predict flow volume changes in geothermal reservoirs toward a goal of estimating the time of thermal breakthrough in such systems. In the upcoming months, work will focus on this problem, using Fenton Hill tracer data to explain the dynamic nature of flow dispersion.

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Modeling the Use of Reactive Tracers to Predict Changes in Surface Area and Thermal Breakthrough in HDR Reservoirs

by

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Abstract:

We have simulated the use of three "idealized" tracers injected into a HDR reservoir by implementing a particle tracking algorithm in GEOCRACK, a discrete element reservoir model. One "ideal" tracer is non-reactive and serves as a standard for comparison with the other two tracers. The second "ideal" tracer has equilibrium adsorption properties that cause a retardation of tracer movement proportional to the surface areas of flow paths. The third "ideal" tracer is a reactive tracer that thermally degrades at a rate proportional to temperature. These three tracers, used simultaneously during long term heat extraction, demonstrate the possibility of measuring changes in heat exchange surface, and predicting thermal breakthrough before temperature decline can be measured at the outlet. This work shows that if real tracers with appropriate chemical properties can be identified and tested, these tracers could provide valuable information on changes in surface area and temperature characteristics of liquid dominated fractured geothermal systems.

Description of simulated tracers:

GEOCRACK applies a particle tracking algorithm to an impulse of tracer particles at the reservoir inlet. Generally, the tracer particles move with the velocity and flow fractions of the fluid, splitting and recombining at flow intersections. In each tracer time step the particles move discrete distance increments with two components. One component is the average fluid velocity. The other component simulates dispersion. Dispersion in GEOCRACK is modeled by Taylor diffusion, which is a based upon a parabolic fluid velocity profile (Taylor 1953). The dispersion component of particle movement is: $x_d = Z\sqrt{2D_L \Delta t}$ where Z is a normal distribution with a mean of zero and a variance of one, D_L is the coefficient of longitudinal diffusion, and Δt is the time step (Reimus 1995). For flow between parallel plates $D_L = D_b + v^2 a^2 / 210 D_b$, where D_b is the Brownian diffusivity, v is the average velocity, and a is the joint aperture (Kessler and Hunt 1994). In addition, tracer particles may be influenced by adsorption and thermal degradation.

Neglecting chemical and temperature dependencies, the movement of the idealized adsorbing tracer is slowed in simulated transport by a retardation value proportional to the surface area of a flow path, and inversely proportional to the fracture aperture. The equilibrium adsorption slowing the transport of particle is described by a retardation factor: $R = 1 + 2K_a / a$ where the velocity of a particle is divided by the retardation factor R, K_a is a distribution coefficient, and a is the fracture aperture where $2/a$ is the ratio of volume to surface area in a fluid element (Freeze and Cherry 1979). Thus, as the surface area of a flow path increases, and as its aperture decreases, more tracer particles exist within proximity of fracture surfaces, and the tracer particles move more slowly due to adsorption.

A thermally degrading tracer is modeled by the temperature dependency relation from Arrhenius' Law, where the tracer concentration is reduced by an exponential decay dependent on temperature. The simulated decrease in concentration is determined by a reaction rate constant: $k = k_0 e^{-E/RT}$ where k_0 is an empirically determined frequency factor, E is the activation energy of the reaction, and RT is the product of the gas constant and absolute temperature (Lenenspiel 1972).

Since GEOCRACK couples the deformations due to hydraulic pressure and thermal strain with the state of stress, fluid volume and flow distribution change as the reservoir cools. Therefore, the residence time and dispersion of a completely non-reactive tracer also changes during heat mining. However, using the non-reactive tracer as a standard for comparison, changes in the degrading and adsorbing tracers qualify and quantify changes in the surface areas and temperature characteristics of active flow paths.

Comparison of reactive tracers to the non-reactive tracer:
The simulation and use of an adsorbing tracer is straightforward, as long as the sorbing properties of the tracer under reservoir conditions can be experimentally determined. Generally, the delay between the peak of the sorbing and non-reactive tracer is proportional to the total surface area of active flow paths. Thus, the delay between the peak of a non-reactive tracer and the peak of the sorbing tracer is a measure of the surface area of the active flow paths. However, the thermal deformation of fracture apertures influences the response because the distribution of tracer particles in proximity to fracture surfaces is considered in the tracer algorithm.

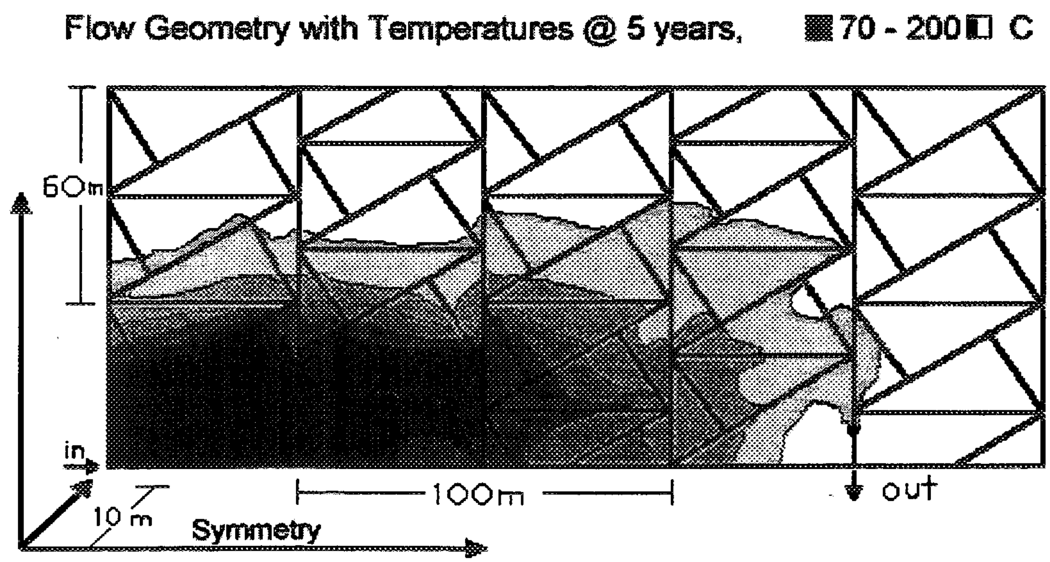
Similarly, the transport of a thermally reactive tracer is influenced by the thermal dilation of flow paths. At a constant flow rate, thermal deformation slows the velocity of tracer because the average fluid velocity decreases in paths with larger cross sectional areas. This causes later initial arrivals, later peaks, and longer residence times in subsequent tracer tests. Still, the difference between the reactive and non-reactive tracers may be compared since they undergo the same changes in flow velocity and distribution. As reservoir flow paths cool, the difference between the normalized return of the non-reactive and thermally reactive tracers decreases and approaches zero. The rate of change in the difference between the two tracers may be used to predict thermal breakthrough.

Discussion:
It is very important to understand the properties of reactive tracers in order to interpret results. In the following simulations the tracer properties were selected for the purpose of illustration. In the model they are described by coefficients in mathematical relationships. In real application, selecting tracers for transport in specific reservoirs and determining their properties under reservoir conditions before subsequent field testing will not be easy. Tracers will need to be customized for the temperature, chemistry, and fluid residence times of actual reservoirs. One unique advantage of HDR reservoirs is that the chemistry and pH of the fluid may be influenced or controlled, especially under closed loop operation, to control the properties of reactive tracers.

The influences of changes in fracture apertures, fluid residence times, and changes in flow distribution make the results of tracer tests even more difficult to interpret. For example, while a thermally degrading tracer can be used to determine "the characteristic temperature" of dominant reservoir flow paths (Adams and Davis, 1991), a short residence time at high temperature might not be distinguishable from a longer residence time at a somewhat lower temperature. GEOCRACK predicts an increase in fluid residence time is likely during heat mining if the injection rate is held constant. Only thermally reactive tracers with relatively large activation energies and large frequency factors are reactive within a narrow and limited temperature range. Such tracers may not be available. To compensate, using two thermally reactive tracers with different properties simultaneously might provide additional information to mitigate this dilemma.

Illustrations:

Figure 1 illustrates a reservoir simulation setup including size, flow path geometry, and temperature contours after 5 years of a constant injection flow at 12.2 m^3/day. Figure 2 plots the outlet temperature with time for the flow injected at 70 C into this simulated fractured system initially at 200 C. Figure 3 shows the change in fluid volume due to the thermal contraction of rock. Figure 4 is the change in non-reactive tracer response due to heat mining. Figure 5 shows the difference between the non-reactive tracer and the sorbing tracer at 10 years. Finally, figure 6 demonstrates that the difference between the reactive and non-reactive tracers decreases as the simulated reservoir cools.



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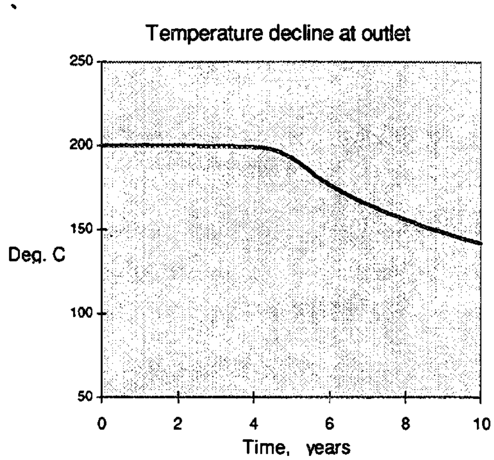

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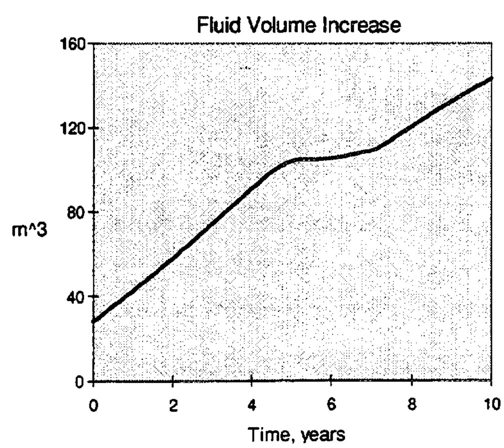

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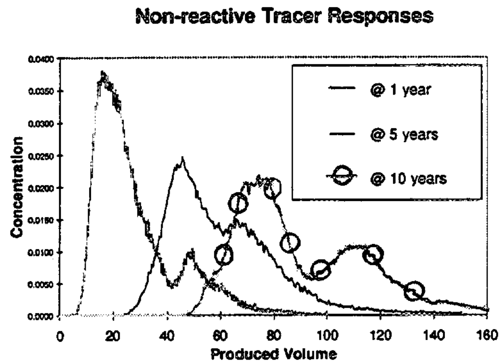

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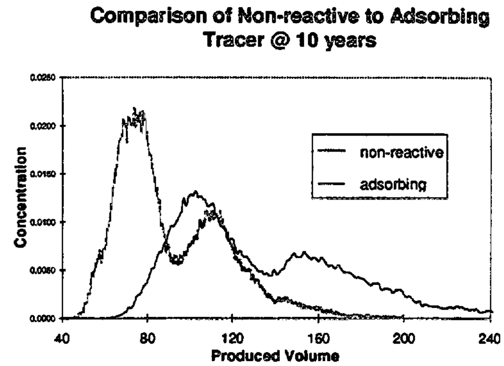

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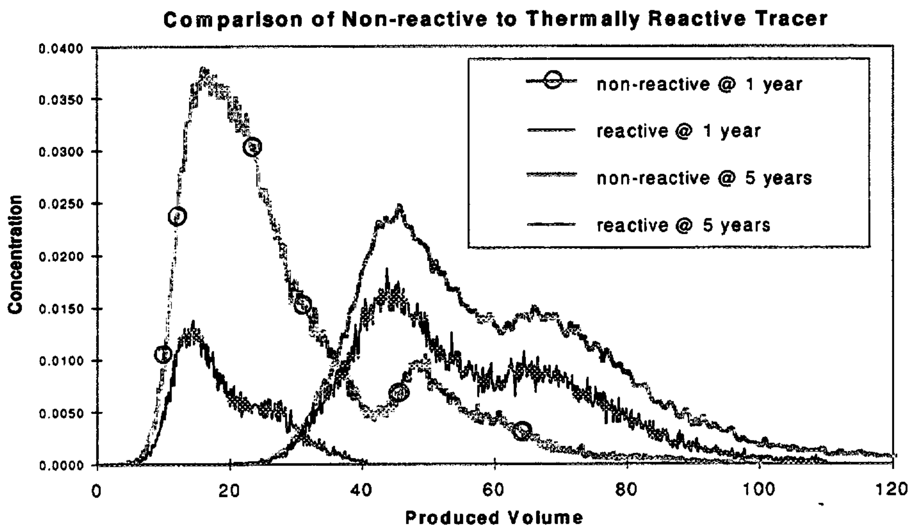

Figure 6.

Acknowledgments:
Thanks to Paul Reimus and Tim Callahan. Thanks to EES-4 and Los Alamos National Laboratory for supporting this work.

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Detailed Joint Mapping at Fenton Hill, NM

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Microearthquakes from selected subregions of the Fenton Hill reservoir (experiment 2032) fall into isolated, planar- and linear-shaped clusters of dimension 20 to 100 m. Straight edges bound the planar clusters, which resemble filled parallelograms. The planar clusters represent shearing joints and their straight edges develop along intersections with aseismic joints. Similarly, linear-shaped clusters represent intersections of otherwise aseismic joints. Thus, the shapes of microearthquake clusters constrain the geometry of seismic and aseismic joints. Aseismic joints are unfavorably oriented for shear slip within the stress field, but may be favorably oriented to open under pressure and become important components of the fluid-flow network.

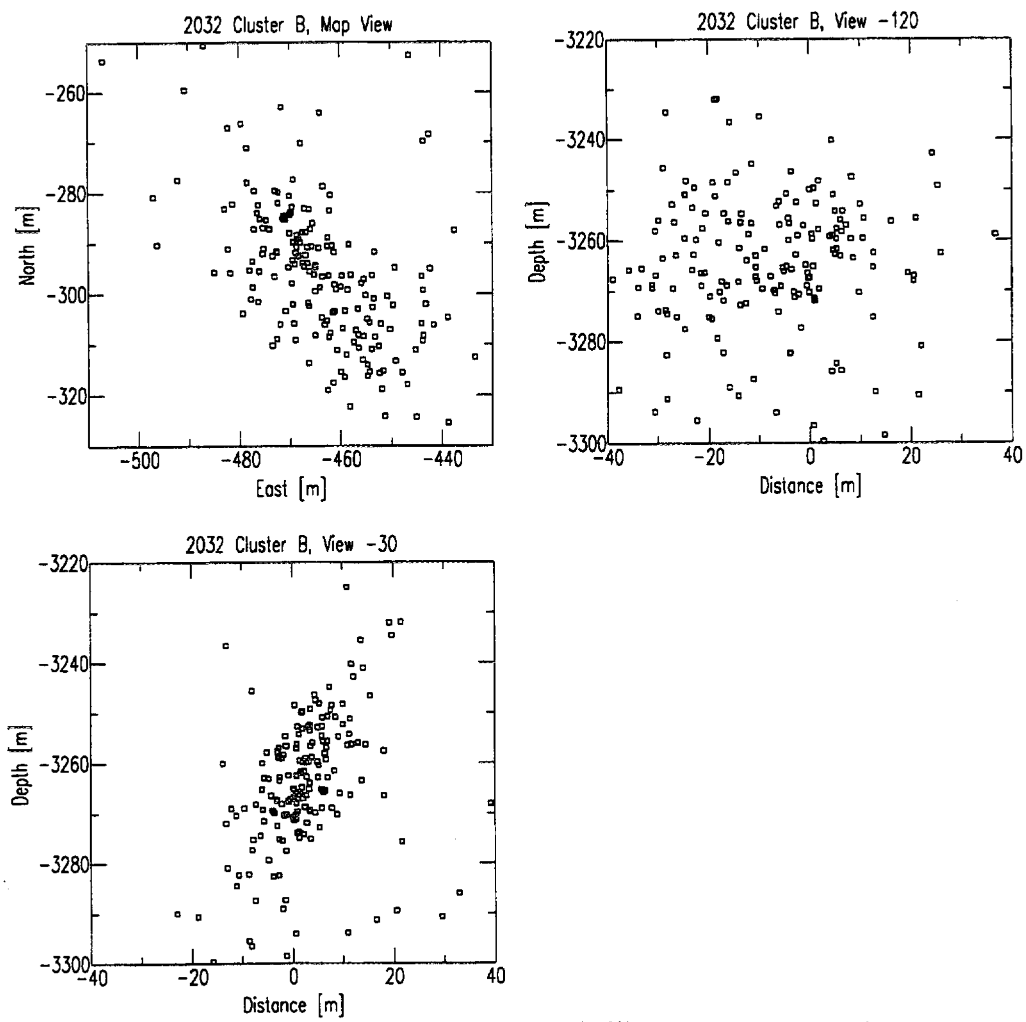

Figure 1: Cluster locations calculated during routine processing. Depth section view angles clockwise from north.

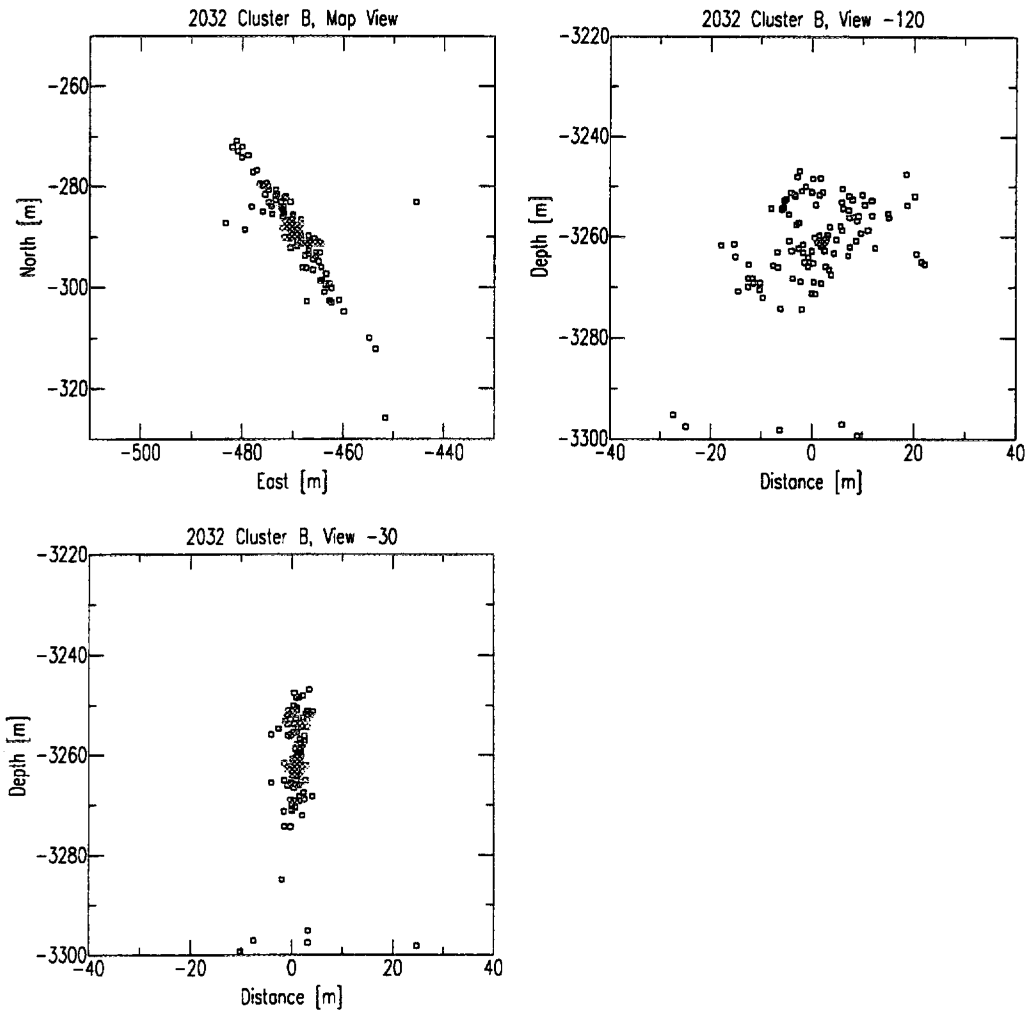

Figure 2: Cluster locations after precise arrival time determination, taking advantage of similar waveforms.

The Load-Following Potential of an HDR Geothermal Reservoir

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The 6-day cyclic Load-Following Experiment (LFE) conducted in July 1995 has verified that a hot dry rock (HDR) geothermal reservoir has the capability for a significant, and very rapid, increase in power output upon demand (Brown, 1996). The objective of the LFE was to study the behavior of the Fenton Hill HDR reservoir in a high-backpressure baseload operating condition when there was superimposed a demand for significantly increased power production for a 4-hour period each day. In practice, this enhanced production was accomplished by a programmed decrease in the production well backpressure over 4 hours, from an initial value of 15.2 MPa (2200 psi) down to about 3.4 MPa (490 psi). This rapid depressurization of the wellbore during the period of enhanced production resulted in the draining of a portion of the fluid stored in the pressure-dilated joints surrounding the production well. These joints were then gradually reinflated during the following 20-hour period of high-backpressure baseload operation. In essence, the HDR reservoir was acting as a fluid capacitor, being discharged in 4 hours and then slowly recharged during the subsequent 20 hours of baseload operation. In this mode of operation, there would be no increase required in the reservoir size or number of wells for a significant amount of peaking power production for a few hours each day.

Although we were able to achieve a power augmentation of 65% for a period of 4 hours each day, there appear to be several engineering approaches that could increase this peaking factor even more. For instance, if the ambient pressure of the HDR reservoir were to be increased to the maximum allowable pressure without reservoir growth, this would correspondingly increase the fluid storage in the pressure-dilated joints surrounding the production well, providing additional drainage volume for the transient periods of surging flow. In addition, since the properties of the fluid in an HDR reservoir are under our control, the composition of the fluid could be altered to allow a continued pressure drawdown below 3.4 MPa, down to the vapor pressure of the water (1.25 MPa at 190°C). In our case, this could be done by adding an appropriate amount of ammonia to the circulating water to prevent the evolution of the dissolved CO_2 known to be present.

FLUID STORAGE IN PRESSURIZED JOINTS NEAR THE PRODUCTION WELL

Based on the results of extensive transient and steady-state flow and pressure testing over the past 10 years, it is apparent that the HDR reservoir at Fenton Hill is comprised of a sparse, multiply interconnected set of joints in a very large volume of hot crystalline rock. The ratio of fluid to rock volume is of the order of 10^{-4}. Within the body of the HDR reservoir, fluid is stored primarily in dilated joints that are mostly jacked open by fluid pressures that are well above the least principal earth stress. Therefore, the main component of the reservoir fluid storage arises from the elastic compression of the rock blocks between pressurized joints.

The pressure gradient across the body of the reservoir, from the inlet to near the outlet, is reasonably gradual. However, for the 10-meter ± region surrounding the production wellbore, the pressure gradient steepens markedly as the pressure drops to the level of the imposed pressure in the wellbore (imposed by the backpressure regulating valve at the surface). As a result, the joints are progressively more tightly closed by the earth stresses as the flow converges toward the pressure sink represented by the wellbore. This near-wellbore pressure gradient for the production well can be inferred from the set of transient shut-in pressure recovery profiles shown in Figure 1 (DuTeau and Brown, 1993). When the production well was suddenly shut-in, the pressure measured at the surface (a direct measure of the downhole reservoir outlet pressure) rose from 9.65 to 20 MPa in less than 3 minutes, indicating that a high pressure level existed in the joint network very close to the borehole production interval.

Conversely, when the production well backpressure is suddenly *decreased* from an elevated level of 15.2 MPa, this steep pressure gradient-region rapidly extends radially further into the body of the reservoir, effectively depressurizing and draining a significant zone of fractured rock surrounding the production borehole. After 4 hours of continuous low-backpressure operation, this zone of depressurized joints probably extends radially outward several tens of meters from the borehole.

THE JULY 1995 LOAD-FOLLOWING EXPERIMENT

Starting on July 3, 1995, the Fenton Hill HDR reservoir was tested in a cyclic production mode for six consecutive days. This series of cyclic tests (the LFE) was begun from a well-established steady-state high-backpressure operating condition that had been maintained for the previous 18 days (Brown, 1996). Figure 2 shows the last two cycles of the LFE which were conducted in flow control with the production well backpressure continually adjusted to maintain constant production flow rates for the 4-hour and 20-hour intervals, respectively. The mean flow rates for the last cycle were 9.25 l/s for the 4-hour peaking interval at a production temperature of 189°C, followed by 5.83 l/s for the subsequent 20 hours at a production temperature of 183°C. These flow and temperature values indicate a production flow enhancement of 59%, and a power enhancement of 65% during the peaking phase. The time required to increase the reservoir power output from the baseload to the peaking rate was about 2 minutes. Table I presents the reservoir performance data for the sixth cycle of the LFE.

Table I
Reservoir Performance for the Sixth Cycle of the LFE

Averages:	4-hr Peaking	20-hr Baseload	24-hr Overall
Injection Flow, l/s	8.16	8.18	8.18
Production Conditions:			
Flow Rate, l/s	9.25	5.83	6.41
Temperature, °C	188.7	182.9	183.9
Thermal Power, MW	6.12	3.72	4.11

The average production flow rate for the last 24-hour cycle was 6.41 l/s, 3.9% greater that the steady-state level of 6.13 l/s existing on the morning of July 3, just prior to beginning the 6-day LFE. Similarly, the mean production temperature was 183.9°C, up slightly from the 182.7°C level existing on July 3. These average flow and temperature levels during cyclic operation show that there was a meaningful overall enhancement in the reservoir performance when compared to preexisting steady-state levels at a constant backpressure of 15.2 MPa. This enhancement was enough to almost completely compensate for the flow decrease resulting from an increase in back-pressure from 9.65 to 15.2 MPa and the accompanying decrease in reservoir driving pressure drop.

CONCLUSIONS

A unique new method for operating an HDR reservoir to produce both baseload and peaking power has been experimentally demonstrated. In initial tests of this concept, an enhanced power output of 65% for a period of 4 hours each day was obtained. This enhanced power output was obtained from a level of baseload operation that was within only a few percent of the previously determined optimum steady-state operating conditions. The demonstration of this load-following capability could greatly increase interest in HDR geothermal systems by electric utilities because providing for surges in electric power demand is one of their major concerns at present.

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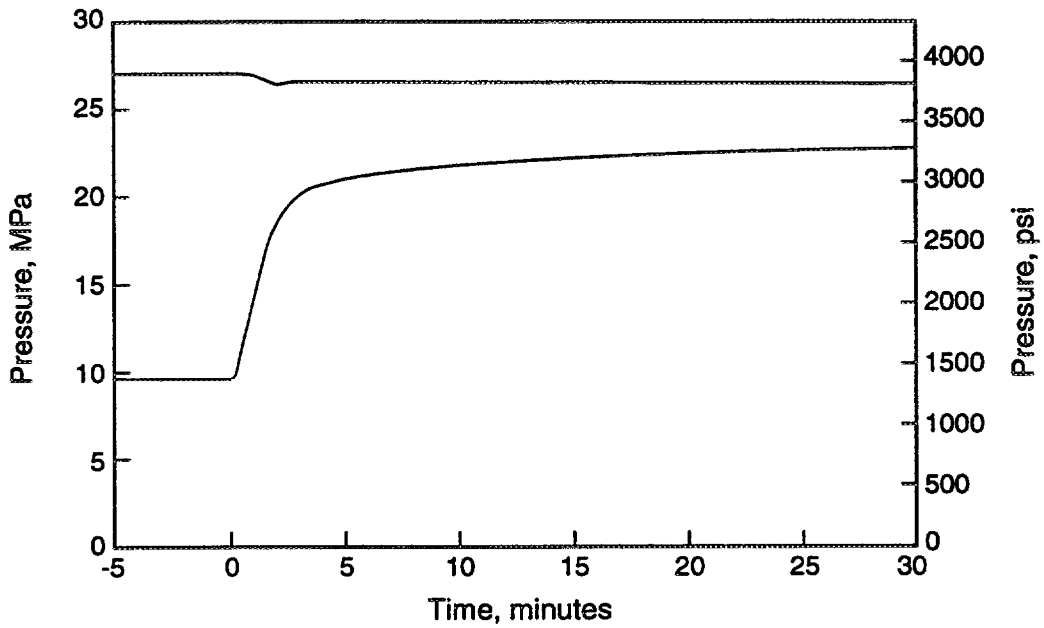

Figure 1. Transient Shut-in Pressure Profiles for the Injection and Production Wells

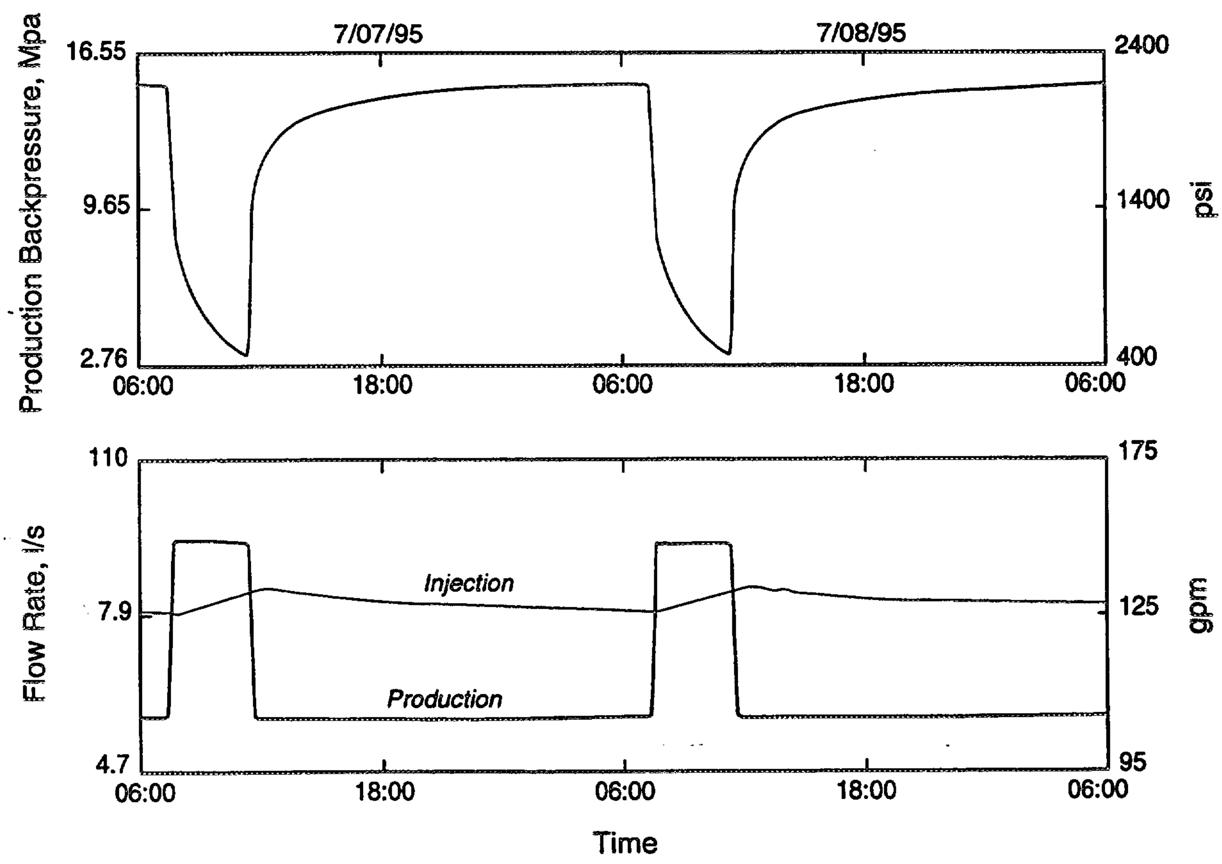

Figure 2. Last Two Cycles of the Load–Following Experiment

Session 5:
Economics and Legal Issues

Session Chair: Isao Matsumaga

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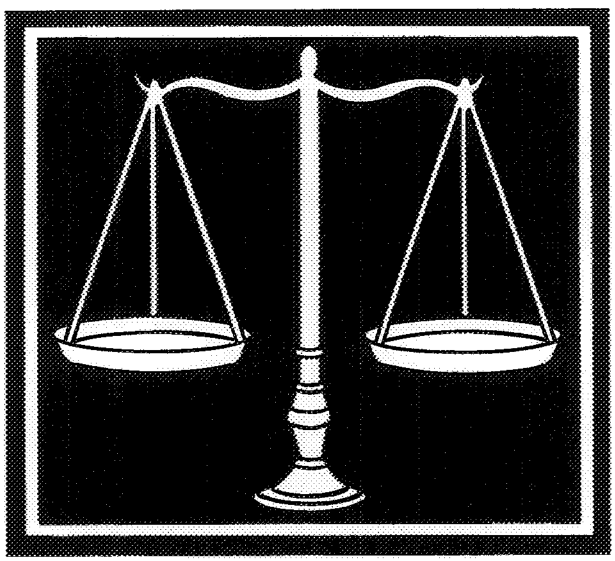

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Economic Analysis of HDR Power Plants with special reference to the European HDR-Site

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Summary

The recent activities at the European HDR-Test Site, show encouraging results with regard to an economic energy extraction. The site is located in a geographical Graben structure (Upper Rhine Graben) with a high geothermal gradient in the upper 1.5 km depth and a temperature exceeding 168 • C in a 3.8 km depth. With the experience of previous drilling activities it was possible to reduce drilling costs by a factor of about 2 ; hydraulic stimulation improved the injectivity of the open hole section near the bottom of the hole by a factor of 20 ; the stimulated fracture system extends in excess of 200 m merging with a rock section which was previously stimulated in a second hole ; the pressure respond between the two holes is excellent almost without a time lag ; during production tests the bottom hole pressure was linearly increasing by almost 0.2 production hole (pressure reduction in the production hole is essential in order to achieve a balance circulation (an increase 0.5 • C per day was observed in the productive fracture in 3.485 km depth). Consequently a scientific pilot plant, with two or three production wells and a target production rate around 75 l/s is now being planned.

For an optimised design and performance of the plant a multi-parameter economic model was developed. This model (called HDREC), is a cost benefit model, calculating the costs for the construction and the operation of a HDR-power plant. The structure of a HDR-plant consists of components, which are determined by the geographical and geothermal conditions at a specific site, and the technical criteria defining the design of the plant, which can be manipulated within certain limits in order to optimise the performance of the HDR-reservoir and the powerstation. The central part of the model is the mathematical formulation of the thermal and hydraulic performance of the HDR reservoir : the heat production as a function of time (draw down) and the parasitic energy consumption for the circulation of water through the fracture network of the reservoir are determined. The financial treatment of the model was adjusted to previously developed economic models, which have been applied to the cost evaluation of conventional and alternative energy resources.

The HDR-reservoir is the central component of the circulation system. It is artificially created by massive hydraulic fracturing and consists of stimulated natural joints and newly generated fractures. The volume of rock mass containing this fracture network (hydraulic paths) constitutes the heat-exchanger if a fluid circulation is imposed. Its thermal efficiency is determined by the rock temperature, the size and the geometry of the fracture network and the flow rate of the circulation. The hydraulic resistance of the fracture system can reach quite high values. It is determined by the hydraulic impedance of the network, which strongly depends on the transmissivities of individual hydraulic components of the reservoir. The impedance of the HDR-system, the circulation flow rate and the viscosity of the circulation fluid (water) define the punp requirements. Fluid losses during circulation can be high and thus have to be taken into account.

The performance of the HDR-reservoir is evaluated form analytical models, which predict the thermal, hydraulic and mechanical behaviour of the stimulated multi fracture system. The complex network of hydraulic paths in the reservoir is approximated by a system of inclined, parallel, equally spaced fractures, which are intersected by injection and production wells. The fractures are assumed to penny shaped discs with equal (constant) wide and size. The interaction of neighbouring flow paths on heat-extraction is considered.

The hydraulic behaviour of the HDR system is definded by the impedance of the HDR reservoir, the geometries and locations of injection and production wells. The buoyancy pressure favours the circulation and reduces the parasitic power demand. The pressure losses are derived from analytical hydrodynamic models describing the fluid flow in pipes (bore holes) and in fractures. The fluid flow within the fracture planes (penny share discs) are described by laminar dipole fluid flow between the experiments in crystalline rocks within artificially created fracture systems were integrated in the model : pressure losses occur at the inlet and outlet of fractures into boreholes and are negligible beyond a critical distance from the boreholes ; the losses are caused by fluid friction at the fracture surface as well as by kinematic effects at the intersection of the fracture with boreholes ; they depend on the flowrate of the circulation as well as on the fluid pressure in the reservoir (pressure dependency of the fracture transmissivity). The fluid losses during circulation result mainly from losses into hydraulic active natural joints (losses due to permeation into the host rock are negligible).

The thermal behaviour of the HDR system is predominantly determined by heat extraction form the host rock. The heating of the circulation fluid in the injection borehole and its cooing in the production borehole are of minor importance if a continuos long-term circulation is considered and therefore can be neglected. The heat extraction is calculated for circulation through a multi-fracture system. The pressure potential between inlet and outlet as well as the superposition of cooling effects betweeen adjacent fractures are taken into account.

Additional features of the computer code HDREC include the economic cost evaluation representing the second key part of the computer program. The economic cost evaluation is based upon the Net Present Value and the Present Value methods. The cost include the investment and the operation costs. Revenues are derived from the sale of the produced electricity solely. Financial schemes and financial criteria are considered. The criteria are evaluated with respect to the year of the beginning of the commercial energy production.

The model was applied to the originally three candidate sites in Europe for the conceptual design of a scientific HDR plant : Rosemanowes/England, Urach/Germany, Soultz-sous-Forêts/France. The following parameters defining the subsurface conditions at the specific site were used in the model : depth of crystalline basement, geothermal gradient, rock-temperature, in-situ stresses, hydraulic properties of joints, physical properties of rocks, geochemical composition of rocks and formation water. The technical design criteria for the plant (not dependent on the location of the site) are : production rate, heat/power conversion system. The result of this component aided comparison is, that the location at Soultz-sous-Forêts has the best natural qualification for futher HDR-development in Europe.

OPTIMIZATION OF HOT DRY ROCK GEOTHERMAL POWER PLANT

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This study deals with simulation of heat extraction from hot dry rock (HDR) and estimation of power plant output, and investigation on geothermal resources in the Kansai area in central Japan. Results of the study indicate that HDR with a diameter of 2km, a thickness of 1km and temperatures higher than 250℃ is needed to provide 55MW of electric power for 20 years. The cost of power generation is approximately $0.1 per kWh in the case where an underground system is built in 300℃ HDR at a cost of $300 million.

Potential geothermal resources in the Kansai area are estimated at several millions to tens of millions of kW.

The concept of hot dry rock power generation is shown in Fig.1.

Fig.2 shows the results of the hot water flow analysis under typical conditions. The figure, showing the flow line of hot water, indicates that the majority of the water injected is recovered, with a portion lost out of the fractures. Here the flow line at the boundary between the hot water recovering area and hot water lost area is also analyzed. The inner side of the flow line is an effective heat transfer area.

Fig.3 shows the results of the heat extraction analysis. This shows the change of the temperature of water extracted from HDR. In this chart the total volume of rock is uniformed, and the number of fractures is a parameter. In the case of 40 fractures, it can be seen that nearly constant water temperature is possible over a long period. With less number of fractures, water temperature becomes lower 10 and 20 years later. The axis on the right hand side is the amount of heat extracted.

In HDR power generation, water loss in the system is critical. So HDR power plants should be designed so as to minimize the water loss by applying air condenser, etc.

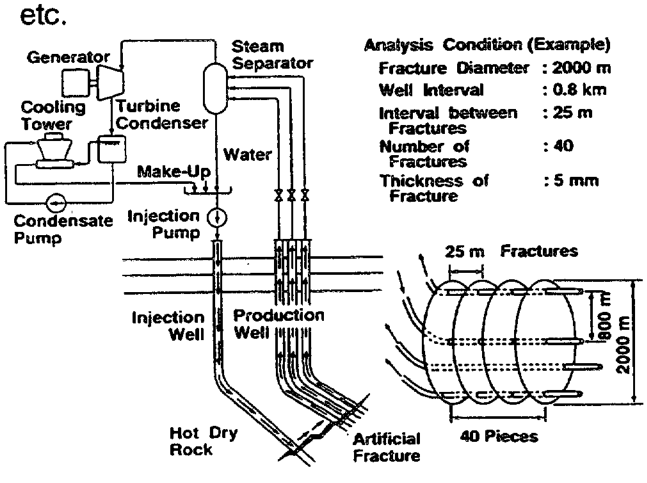

Fig.1 The Concept of HDR

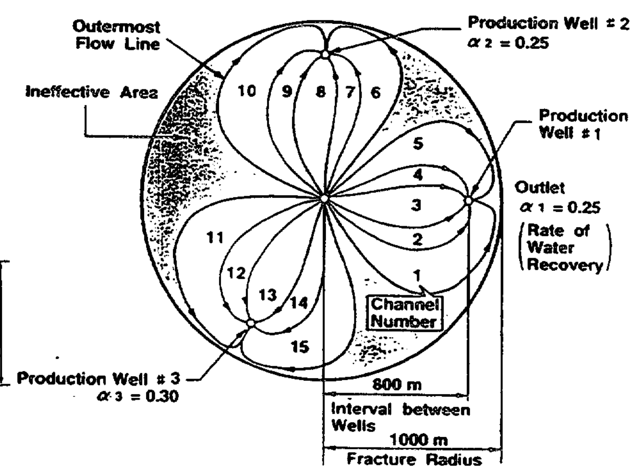

Fig.2 Example of Hot Water Flow Analysis

The generating cost analysis for each case is shown in Fig.5. The method of calculation used in this cost analysis is the same as the one shown in Fig. 3. If the temperature of HDR is 300℃, and if the construction cost of underground facilities is $300 million, the generating cost is about 0.1 $/kWh.

Geothermal resources in the Kansai area was investigated from reference papers and a simulation program. (Fig.6) As a result, the geothermal resources are estimated at several millions to tens of millions of kW.

HDR seems promising as one option in the utilization of natural resources for power generation.

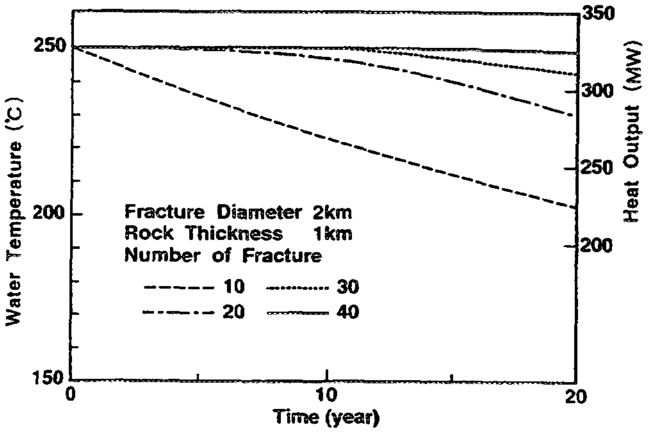

Fig.3 Example of Heat Extraction Analysis (Water Temperature)

HDR with 2kmφ×1km, 250℃ is needed to provide 55MW of electric power for 20 years

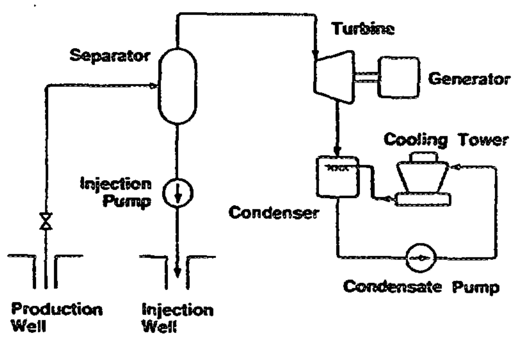

Fig.4 Single Flash Cycle

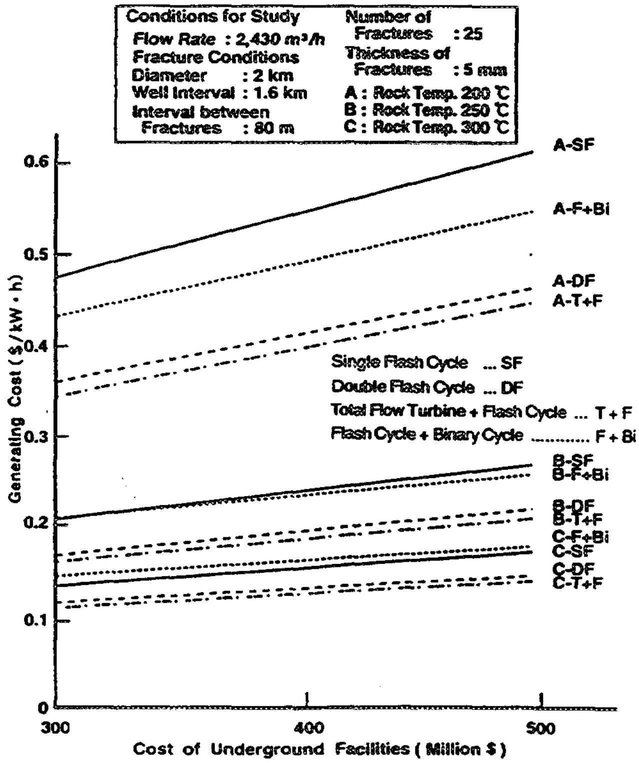

Fig.5 Generating Cost Analysis

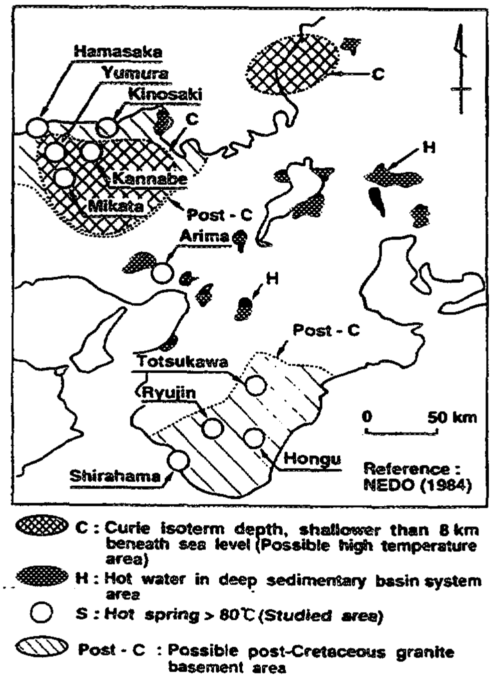

Fig.6 Geothermal Energy Resources Distribution in the Kansai Area

The Impacts of Reservoir Performance and Drilling Costs on Heat Mining

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With today's low energy prices and forecasts of abundant fossil fuel supplies well into the next century, heat mining in low- to mid-grade areas will require significant reductions in reservoir development costs before these resources can be exploited for electric power production. Higher reservoir productivity and/or lower well drilling costs are needed. Possible improvements include: reservoir growth and productivity enhancements due to thermal contraction, drilling systems integration with advanced "lookahead" geophysical characterization of the rock coupled to on-line control of key drilling parameters, and advanced rock penetration concepts.

Figure 1 provides a summary of recent individual well cost data for both geothermal wells and oil and gas wells, along with several correlations and projections (Herzog *et al.*, 1994). The base case/today's technology line represents average conditions for HDR-type well drilling using conventional rotary drilling technology. Figure 1 shows a speculative line for what we have called "linear drilling", where drilling costs for wells deeper than about 4 km no longer follow the exponential behavior of the oil and gas average line -- rather costs become linear in depth at this point. New enabling drilling technologies could shift the cost versus depth relationship from its current exponential dependence to a more linear dependence. As seen in Figure 1, cost data for ultra-deep holes suggests that such improvements might be attainable, particularly if more robust drilling methods are developed that reduce wear and optimize penetration rates. Advanced penetration concepts, such as flame-jet thermal spallation or water-jet cavitation and erosion drilling methods, employed in a fully integrated, smart drilling system could provide such enabling technologies (see Tester *et al.*, 1995).

While recognizing the uncertainties of such speculation, it is interesting to see what happens to predicted heat mining development costs with advanced technologies. In Figure 2, the total U.S. resource is divided into 5 classes or grades, each corresponding to an average gradient between 80 and 20°C/km. This amounts to a total supply of about 42,000 GW_e for the U.S. from heat mining for a 20 year period (for reference, the current U.S. generating capacity is about 700 GW_e). For each class, the bar graph in Figure 2 compares breakeven electricity prices for three heat mining economic scenarios:

(1) today's hydrothermal reservoir productivity levels with today's drilling technology and costs

(2) advanced reservoir productivity levels (order of magnitude greater than today's hydrothermal) with today's drilling technology and costs

(3) today's hydrothermal reservoir productivity levels with advanced linear drilling technology

It is important to note that, to date, man-made HDR reservoirs have not been able to replicate completely the performance of commercial hydrothermal reservoirs. For example, to achieve commercial levels of reservoir production, a 5- to 10-fold reduction of flow impedance from Fenton Hill's (a high-grade HDR reservoir) current levels is required with acceptable water losses. Clearly, more fundamental engineering experience is required before HDR reservoirs can be constructed in an economical fashion. Work in the U.S. and Europe has demonstrated that sufficiently large fracture systems in low permeability rock can be hydraulically stimulated. However, more knowledge of how to create low impedance connections to these fracture systems with contained water losses is required before acceptable productivity levels can be routinely engineered. The key implication here is that more time, effort, and funds should be invested in field demonstrations of heat mining.

Figure 2 shows that for the high-grade classes (60-80°C/km) the effect of advanced drilling technology, while significant, is not as striking as for the lower HDR grades (20-40°C/km) where such technology leads to the economic feasibility of heat mining in current energy markets. Introducing advanced reservoir productivity also has dramatic effects, but lags behind the impact of lower drilling costs for most HDR classes, as well as for hydrothermal systems.

In order to realize these ambitious goals, more R&D effort needs to focus on such advanced drilling methods. The U.S. has started a National program to promote Advanced Drilling and Excavation Technologies (NADET) which has as its main objective to develop technologies within the next seven years capable of substantial cost reductions for drilling, excavation, and mining applications (NADET, 1994). Hopefully such initiatives will lead to more international cooperative efforts to develop enabling technologies for all geothermal energy applications.

References:

Herzog, H., Chen, Z., Tester, J., and Frank, M. (1994). *A Generalized Multi-parameter Economic Model for Optimizing the Design and Performance of Hot Dry Rock (HDR) Geothermal Energy Systems*, Massachusetts Institute of Technology Energy Laboratory report MIT-EL 94-004.

Tester, J.W., Potter, R.M., Peterson, C.R., Herzog, H.J., North, J., and Mock, J.E. (1995). Advanced Drilling and its Impact on Heat Mining. *Proceedings of the World Geothermal Congress,* International Geothermal Association, Inc., Auckland, New Zealand, pp. 1385-1389.

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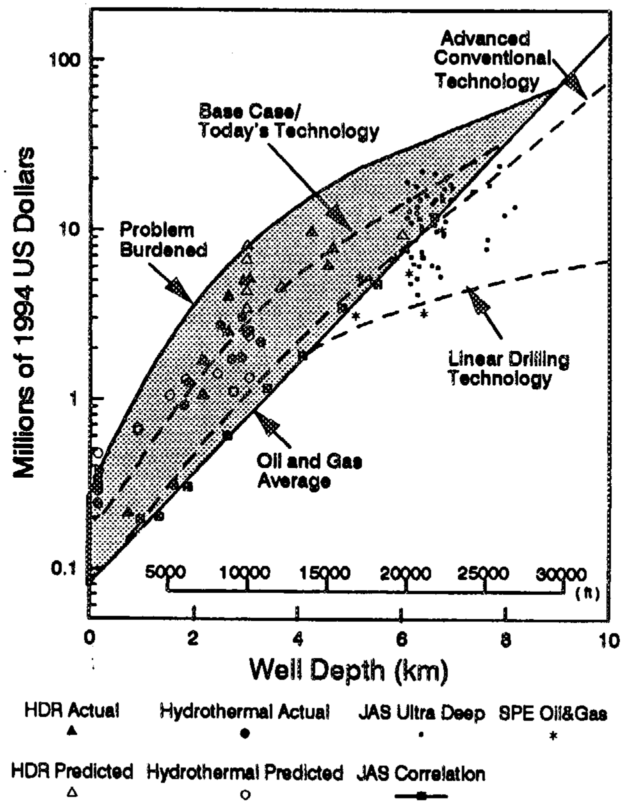

Figure 1. Historical drilling costs for HDR, hydrothermal, oil and gas, and ultra-deep wells. Also plotted are drilling costs for different technology levels. The "problem burdened" line represents the estimated upper limit of drilling costs based on all available cost data for first generation completed HDR wells. The "base case" line approximates the trajectory of the "average" HDR well cost midway between the "problem-burdened" and the "oil and gas average" line which is based on Joint Association Survey (JAS) data for completed oil and gas wells on-shore in the U.S. The "advanced conventional technology" and "linear drilling" lines that represent two scenarios for projected improvements to drilling technology.

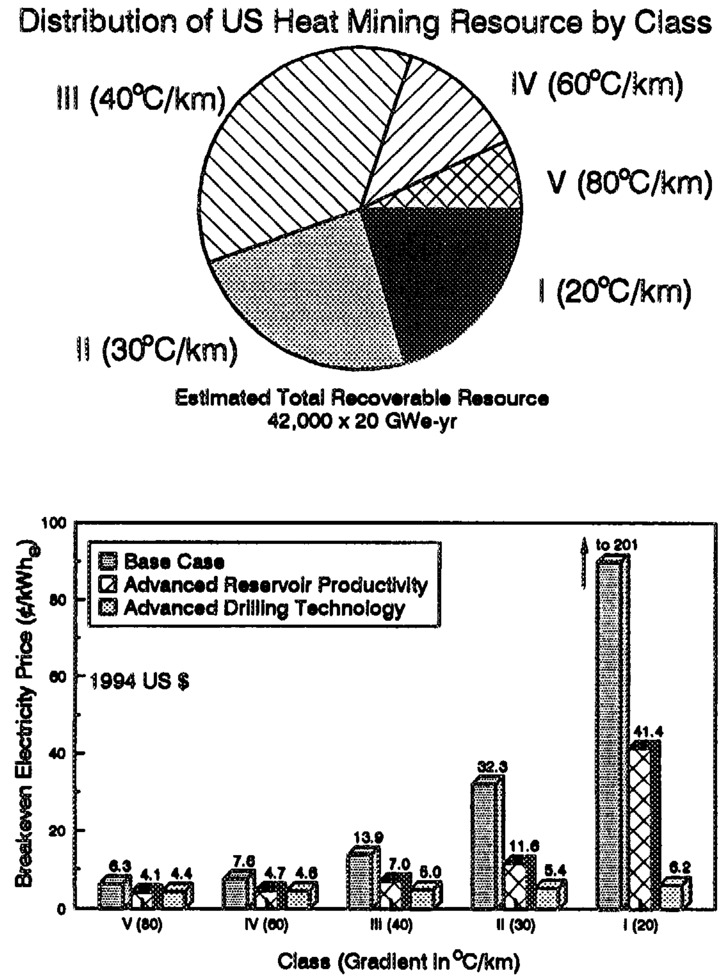

Figure 2. Heat mining resource base for the U.S. Three sets of costs for producing electricity from this resource are shown: hydrothermal reservoir productivities with today's conventional drilling technology; advanced reservoir productivities with today's conventional drilling technology; and hydrothermal reservoir productivities with advanced linear drilling technology.

HDR and Geothermal Law - The Need for a New Legal Vocabulary

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I. INTRODUCTION.

Law trails technology. The development of new technology, bringing about new industries and new products, nearly always outraces the development of the legal rules that will govern the use of that technology in society. Nowhere has that observation proven more true than in the development of geothermal law.[1] However, the formulation of new law is necessary if society is to exploit the economic potential offered by an emerging technology. By giving serious thought to legal concepts at this early stage of development of hot dry rock ("HDR") technology, we may be able to accelerate the process of creating an appropriate legal framework for HDR transactions, such as leases and project financing.

II. ABANDONING OIL AND GAS VOCABULARY.

Much of existing geothermal law, including its vocabulary, was borrowed from oil and gas law. In part this came about due to the superficial similarities between "wet" geothermal development and oil and gas development. In both cases, one drilled a well to reach a reservoir of the sought-after resource, which in the case of geothermal was steam and hot brines. In both cases, if the resource turned out to be present in economically significant amounts, it was then extracted through the well. In both cases it was usually convenient to measure production by the quantity of the physical substance extracted from the well, and to measure royalties in the same way, or by the proceeds from the sale of the produced commodity.

In the case of HDR heat mining, those superficial similarities largely disappear. Instead of a single producing well, an HDR project is a unitary system comprising an injection well, a production well, the connecting reservoir, and, on the surface, the injection pump and the power plant. All elements of the system are indispensable.

In this context, it would serve no purpose for a lease to specify the drilling of a well as the primary development obligation of the lessee, as would

[1] *See, generally* Kostant, "Geothermal Law - the Last and Next 23 Years," 37 *Rocky Mt. Min. L. Inst.* 2-1 (1991); Olpin, "The Law of Geothermal Resources," 14 *Rocky Mtn. Min. L. Inst.* 123 (1968).

commonly be the case in both oil and gas leases and "wet" geothermal leases. A single geothermal steam well with proven production capacity can have, all by itself, demonstrable market value. That is not the case with an HDR heat mining project, where the lessor of the land is unlikely to realize any economic benefit from ownership of less than the entire operational system. Instead of a contractual requirement to drill a well, it may become common for an HDR lease to obligate the lessee to develop a full project.

The lender who finances the development of an HDR project must also recognize that the entire project is the smallest unit with independent economic value. The lender's security documents must, in the event of a default and foreclosure, allow the lender or the purchaser at a foreclosure sale to obtain title to all of the essential components of the project.

The concept of production also will require refinement in the legal documentation of HDR heat mining transactions. Instead of the uni-directional production of steam or brines from a subterranean reservoir, the HDR project endlessly circulates fluids through the cycle of injection, heating, extraction, utilization and cooling. The only "production" in heat mining is the thermal energy conveyed up to the surface and the electrical power into which it is converted. Following a trend that is already emerging in conventional geothermal transactions (where it is increasingly common for lessees to utilize geothermal resources in their own power plants, instead of selling the resources), the most appropriate basis for determining royalties in HDR transactions may be the value of the electricity produced by the project.

III. WHO OWNS THE RESOURCE?

In real property law, ownership of the mineral estate in a property, or the right to extract minerals from the property, may be severed from the basic fee simple ownership of the property (which is commonly, but misleadingly, called the "surface" estate). In a number of cases involving steam geothermal resources, courts have held that where there has been such a mineral severance, the right to exploit geothermal resources belongs to the owner of the mineral estate. The rationale of those decisions is that it is consistent with the general intent of a mineral severance to include geothermal resources in the mineral estate, because steam and hot brines resemble, in the manner of their extraction and their use as a source of energy, fossil fuels such as oil, gas and coal.[2] That reasoning is arguably irrelevant to HDR heat mining, where the geothermal resource is the heat emitted by the ground itself. Indeed, the State of Colorado has legislated that the hot dry rock resource belongs to the surface estate unless it is expressly severed.[3]

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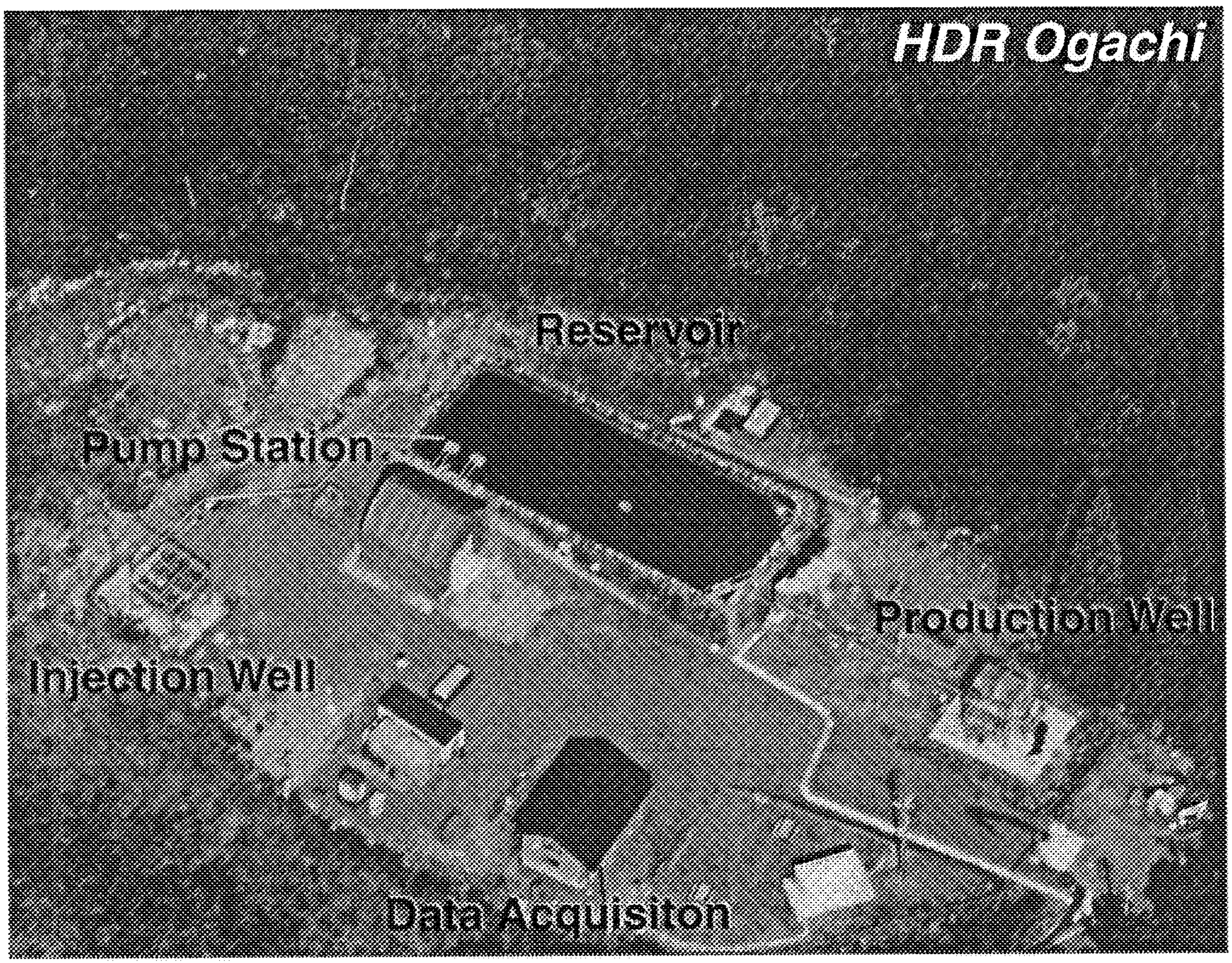
[2] *See, e.g.,* United States v. Union Oil Co., 549 F.2d 1271 (9th Cir. 1977).

[3] Colo. Rev. Stat. § 37-90.5-104(2) (1990).

Session 6:
Ogachi

Session Chair: Jefferson Tester



Outline of the Ogachi project in 1995

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The principal objectives of the 1995 Ogachi project were to reduce the water injection pressure and to improve the water recovery during water circulation tests. At first we redrilled the bottom of the injection well from 1,000 m to 1,027 m to extend the water injection (open-hole) region. After the redrilling, the water injection area was more than doubled. Then the injection well was stimulated by injecting water at a flow rate of 1.7 m3/min and at a wellhead pressure of 18 MPa. A total of 3,400 m3 of water was injected in this stimulation. The production well was also stimulated by injecting water at a flow rate of 2.2 m3/min and at a well head pressure of 18 MPa. The total injected water volume in this stimulation was 4,300 m3. AE hypocenter location distribution during these stimulations showed that the region around the injection and production wells were well fractured.

We conducted a one-month water circulation test between the injection and production wells to confirm the above mentioned redrilling and stimulation effects (see Figure-1). During the circulation test, the water injection pressure decreased to about half of the previous water circulation tests and the injected water recovery from the production well increased to a maximum of 32% (see Figure-2). A tracer test conducted during this circulation test showed that the recovered tracer concentration from the production well increased to one order magnitude higher than that of the previous circulation tests.

Therefore, we conclude that the extension of the water injection area and the stimulation to the injection and production wells are more effective to reduce the water injection pressure and to improve the water recovery.

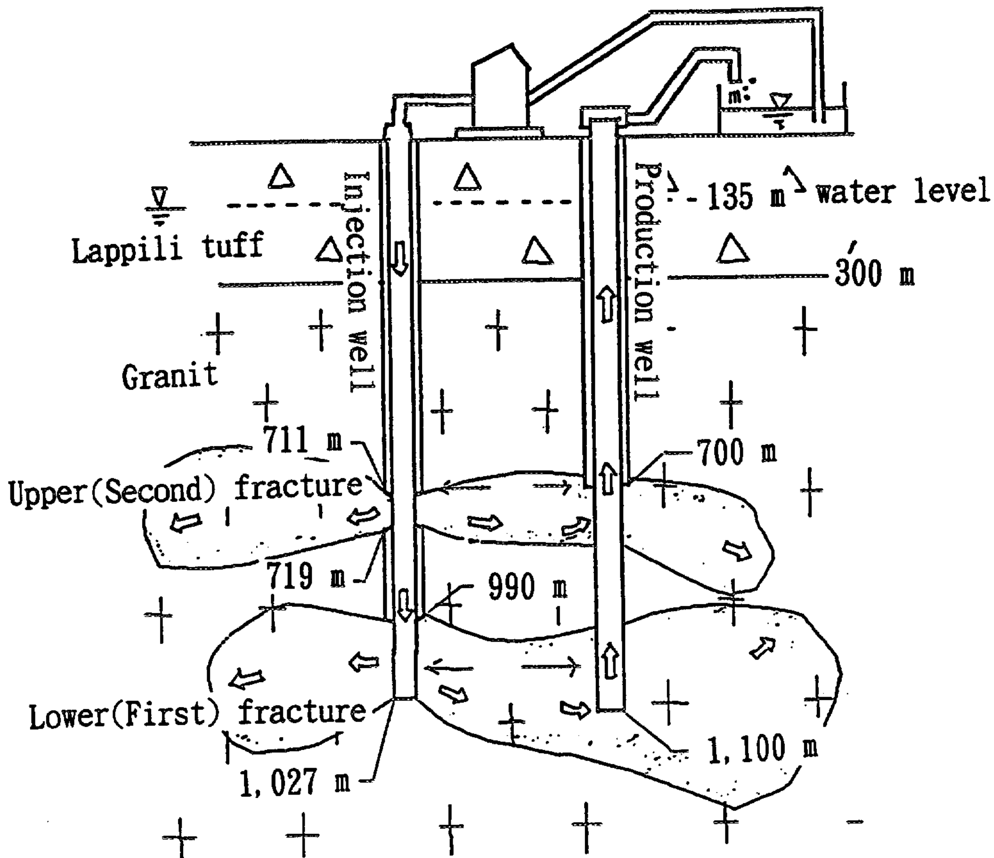

Figure-1. General profile of the Ogachi HDR site.

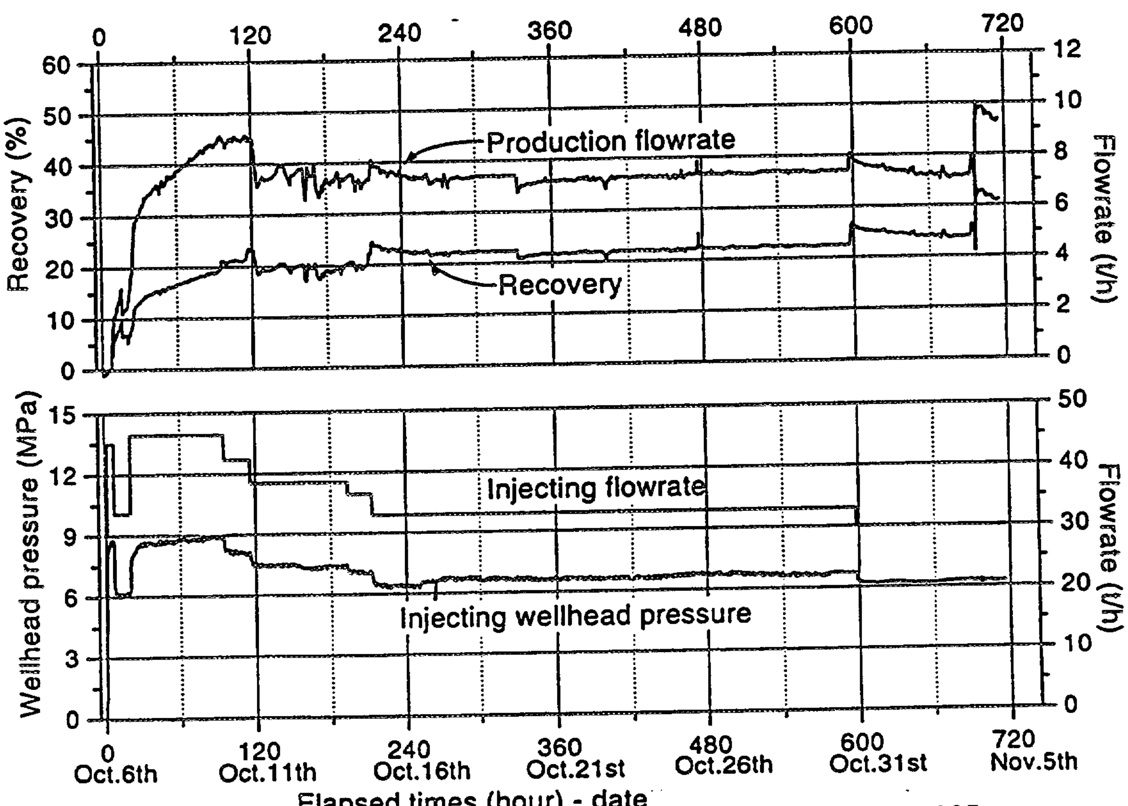

Figure-2. Time history of water circulation test in 1995.

Development and Applications of Measurement Tools for High Temperature Borehole - Joint Location , Water Temperature and Flow rate -

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We developed the High Temperature Borehole Scanner (HTBS) to observe the joints locations along the borehole wall surface and the High Temperature Spinner and Thermometer (HTST) to determine flow rates and temperatures within the borehole. The system consists of a probe, cable, cable drum, laser unit and recorder,(Fig 1, Table 1).

This presentation describes the HTST. (We described the HTBS in at 1990 GRC). Since flow rates at various depths indicate the volume of hot water entering the well from numerous artificial fractures, the HTST provides the data we need to determine how much water is recovered from each of the two fracture layers. The HTST uses a laser probe since the high temperature precludes the use of electronic sensors.

1. The Probe

The probe consists basically of a propeller and a sensing device housed in a waterpro of container. The housing is one meter long and has a diameter of 50mm. The casing is made of stainless steel and the entire unit weighs 10kg. It is sealed for waterproof capabilities up to a pressure of 150kgf/cm2.

Adjacent water flow drives an externally mounted propeller, which in turn, rotates a disc inside the casing. The rim of the disc is perforated with 12 holes at 45o intervals. A solid laser light beam, sent through a cable, passes through the perforations and travels back to the surface at a pulse speed determined by the speed of the rotating disc. Our main problem was to assure synchronization between the propeller shaft outside the casing and the disc inside the casing without allowing any water seepage.

To accomplish this we devised a magnetic drive system. Outside the sealed area, plus magnets are attached to three prongs extending from the propeller shaft. Inside the sealed area, minus magnets are attached to three parallel prongs extending from the disc shaft. We decided on a three point interface because four would add too much weight and two might allow slippage.

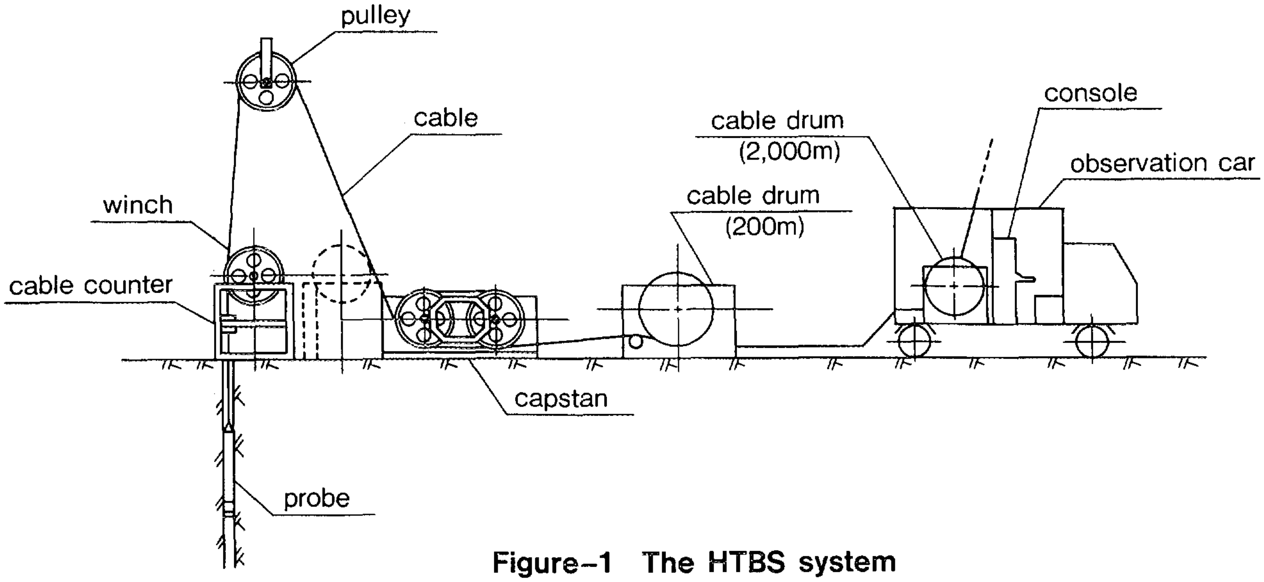


Figure-1 The HTBS system

Table 1. Outline of HTBS and HTST System

		HTBS	HTST
Name		High Temperature Borehole Scanner	High Temperature spinner and Thermometer
PROBE	External diameter	65 mm	50 mm
	Waterproof pressure	200 kgf/cm2	150 kgf/cm2
	Max Temperature	200°C	250°C
	Input voltage	100,200 V,50/60 Hz	–
	Laser	830 nm	1300 nm
	Mirror Rotation	5,000 rpm	–
	Scanning line	525 line	–
	Minimum Direction	1	–
	Minimum Angle	1	–
	Minimum Depth	1 cm	–
	Minimum Temperature	1	0.1°C
CABLE	Length	2,000 m	1200 m
	External diameter	20 mm	2.4 mm
	Waterproof pressure	200 kgf/cm2	150 kgf/cm2
	Optical Glass Fiber	50/125 umGI*4	50/125 umGI*4
	Pipe		incoroy
WINCH	Moter	0.8–840 m/h	0–600 m/h
	Minimum depth	1 cm	1 cm
CONTOROL		Computer	Computer
DEVEROPED YEAR		1989	1995

2. The Cable

The 1,200 meter-long cable is made of a seamless incroy pipe with a diameter of 2.4mm and contains four carbon polymede fiber optic lines and one titanium line. There are two sets of lines for transmitting and retrieving; one set for temperature and one for water flow speed. Each fiber optic line has a diameter of 50/125u mGI. The titanium line was added after a one-month trial showed that the high temperature conditions were weakening the beam.

The titanium line absorbs the exessive hydrogen emitted by the high temperature water and eliminates the hydrogen interference with the light transmission.

3. The Cable Drum

The cable is fed by a rotary joint drum powered by a 100 volt AC motor.

The motor feeds the cable at a speed of from zero to 10 meters per minute and is reversable. An electric pulse meter set to the drum's rotation sends data to the laser unit where it is used to calculate exact depth measurements.

4. The Laser Units

The first laser unit consists of a laser diode with a wavelength of 1.3 umand three measuring devices; a pulse counter, a speed calculator which factors in the probe's vertical movements, and a depth counter which takes its measurements from the cable drum rotation. The second unit uses a 1.3 um laser diode to measure temperatures at 1 meter intervals.

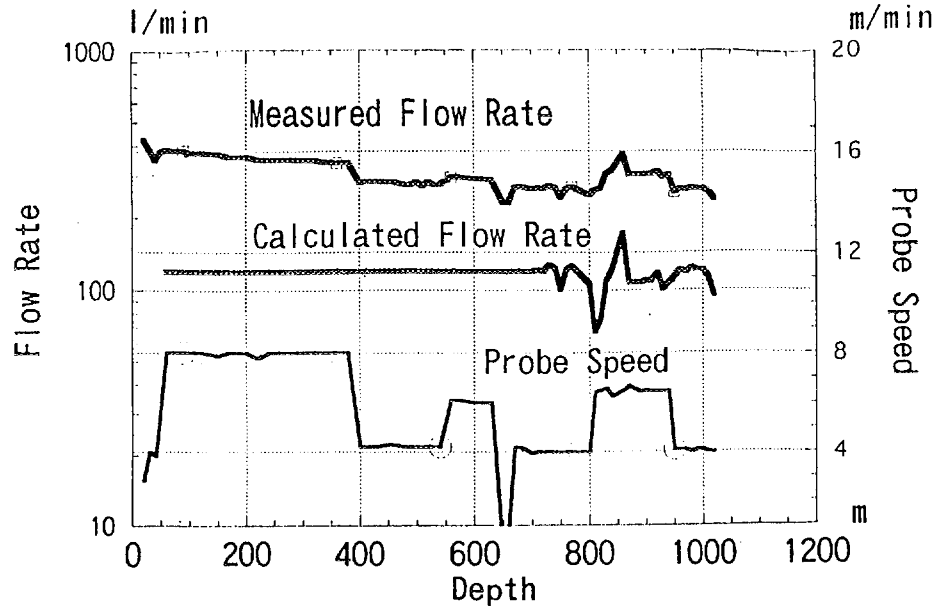
5. The Recorder

A 3-channel anologue graph recorder provides constant data on hydraulic flow velocity, probe depth and probe speed. The temperature data is transmitted directly to a personal computer for analysis and recording.

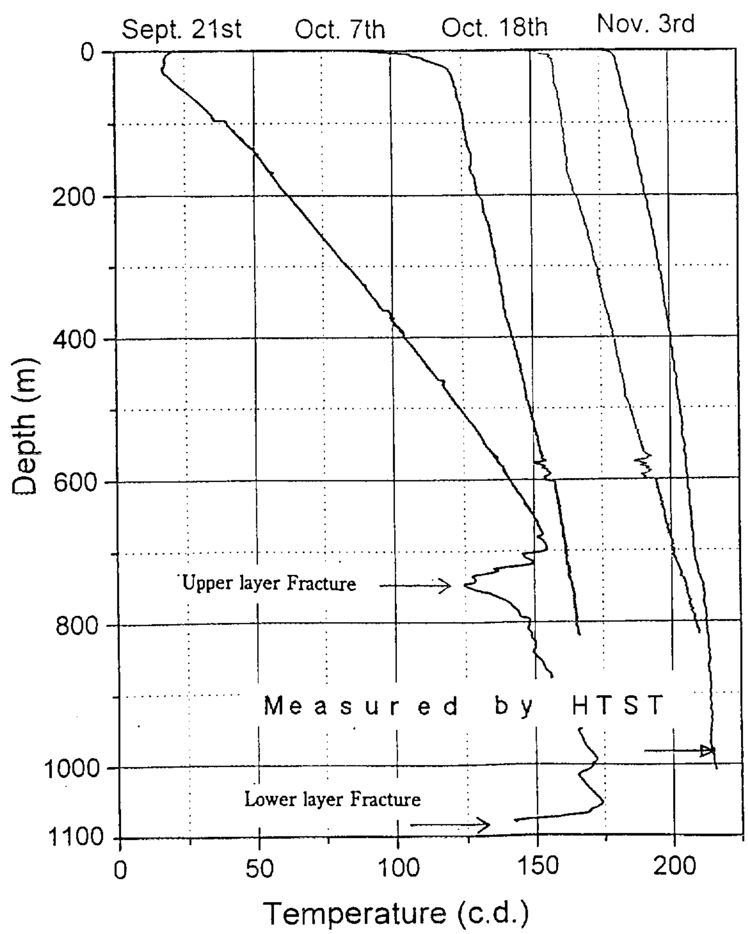
6. Conclusion

We used the HTBS and the HTST at the Ogachi site in a 30-day flow test last November. With these systems we were able to collect valuable information on fracture locations and flow rates at different depths along the production well. We found that of all the recovered water, 90% originated at the lower fracture layer and only 10% at the upper fracture layer, (Fig 2,3).

We now know that it is necessary to make alterations to the injection well in order to channel a greater volume of water through the upper layer. Ideally, we would like to see an equal distribution of recovered water from the two layers. We are now studying methods to redirect the flow distribution and expect to begin new tests next summer. We hope to be able to present some encouraging new data at the next conference.



Figure−2 Probe Speed and Flow Rate



Figure−3 Temperature Changes of Production Well

(1995)

AE hypocenter distribution during hydraulic fracturing and water circulation tests at Ogachi

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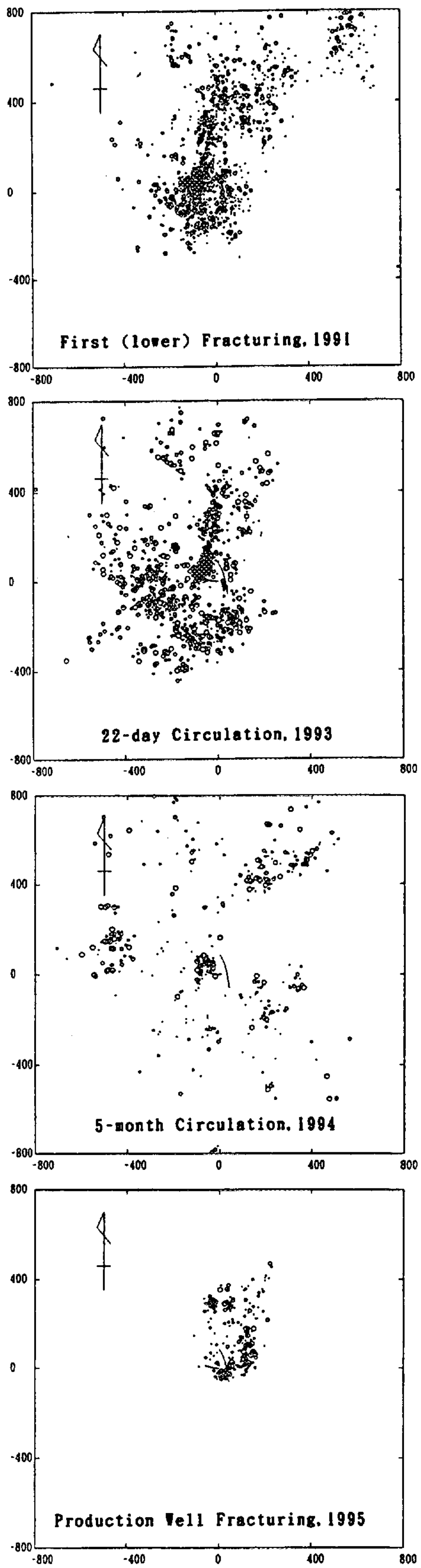
The Central Research Institute of the Electric Power Industry has conducted some hydraulic fracturing and water circulation tests using two 1,000 m deep wells since 1989 at Ogachi, northern Japan. During these tests, AE (microearthquake) events were monitored and many events were located. Figure 1 shows the AE epicenter distributions determined in the major fracturing and circulation tests. A first fracturing was conducted at around 1,000 m depth in 1991 and a second at around 700 m depth in 1992. The AE location distributions during these fracturings have clear trends, i.e., nearly north-south in 1991 and nearly east-west in 1992. Using these artificially created fractures, three water circulation tests were conducted. More than 1,000 AE events were detected during the first (22-day) water circulation test in 1993. In this test, the water injection pressure was still high, nearly equal to that of the previous fracturing and the injected water recovery from the production well was 3%. We can estimate from the AE distribution that the injected water flowed into the lower fracture at first then dispersed to the west. In the second (5-month) circulation test, the water injection pressure was decreased and the injected water recovery increased to about 10% after the production well fracturing. The number (a few hundred) of the observed AE was much smaller than that of the first test even though the circulation duration was about 7 times longer. The AE location distribution didn't have a clear trend and seemed to disperse in all directions. In the third (1-month) circulation test, the water injection pressure decreased to about half of the previous tests and the injected water recovery increased to a maximum of 32% after redrilling the injection well and refracturing the production well. During this test, a small number of AE events were observed and almost no AE were located in a 800 m radius area around the injection well. Some small events were located outside the area.
From the above results, we concluded that the rock around the water injection region was well fractured by many fracturing operations, the injected water flowed gradually smoothly between the injection and the production wells through the fractures and the heat extraction area increased in all directions from the injection well.



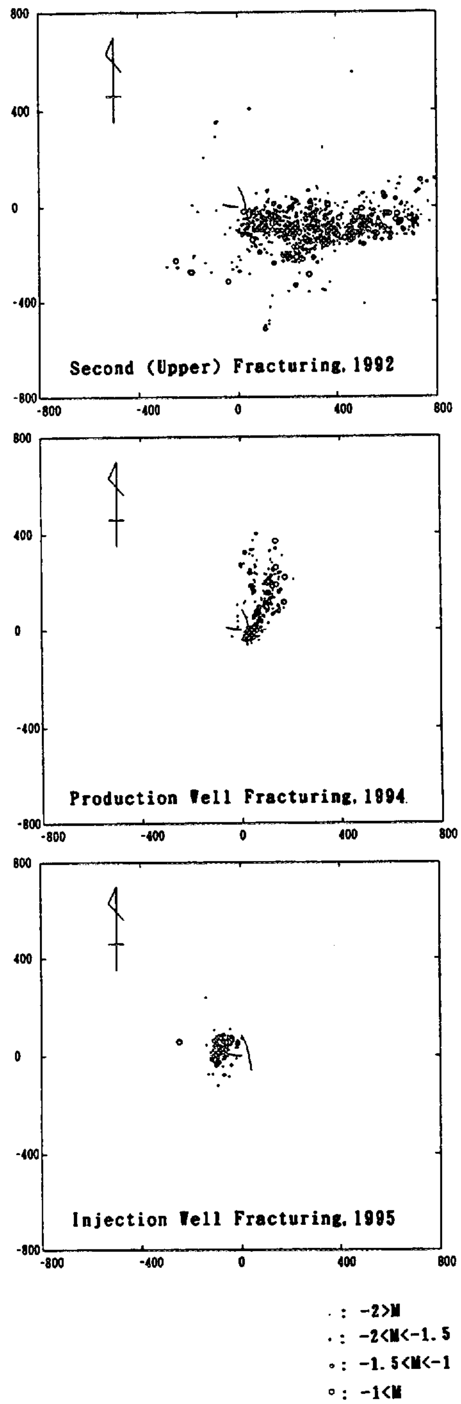


Figure 1 AE epicenter distribution in the hydraulic fracturing and water circulation tests conducted at Ogachi since 1989.

Identification of Reservoir Structure and Stress State from Hypocenter Cloud in Ogachi HDR Field, Japan, by Using Triaxial Doublet Analysis

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Reservoir structure has been identified from the cloud of microseismic sources using the triaxial doublet analysis. A pre-hydraulic fracturing experiment was carried out at Ogachi HDR field of CRIEPI(Central Research Institute of Electric Power Industry), Japan from 5th to 20th of August in 1991. The fracturing test was conducted by CRIEPI, and the water injection was performed 12 times during the period of 17 days. At the depths from 990 to 1000 m where the well is open hole, the total volume of 680 m^3water was injected. The microseismicities associated with the hydraulic fracturing were observed using the downhole triaxial detector installed at the depth of 380m in a measurement well. A total of 2,487 events were observed during the experiment, and the source locations of 256 events with high quality have been determined by using triaxial hodogram method. Figure 1(a) shows the map view of absolute source location. The microseismic events were occurred at the depths from 800 to 1300m.

We have applied the triaxial doublet analysis, which estimates the precise source locations relative to the source location of a reference event, to the doublet (multiplet) observed during the fracturing test. A group or a pair of events with very similar waveforms are called multiplet or doublet, and these similar events are considered to be the expression of stress release on the same fault system. 3 groups (multiplets) and 10 pairs (doublets) of events with similar waveforms were identified in the catalog of located events. Their source location have been relocated using the cross spectrum analysis and the spectral matrix analysis (Moriya et al., 1994). Figure 1(b) shows the relocated source locations. It is suggested that the fractures are extended to upward at the two different locations. We have picked out 3 groups of multiplet, and calculated the structural planes defined from their hypocenters. Figure 2 shows the stereographic projection of estimated structural planes (lower hemisphere). The trend of their strikes is inclined toward NE and NNE, where the overall distribution of the microseismic sources has the similar trend. We have applied the grid test on a moment tensor analysis using P-wave polarities and the S-wave polarization directions to the multiplets in order to evaluate the structural planes if they behave as seismic sources, and to estimate the direction of shear dislocation along the structural planes. As the result of the focal mechanism analysis, it is suggested that all the structural planes behave as a dip slip normal fault or a lateral strike slip fault. Using the strike, dip and slip direction of the faulting planes, the direction of principal stress direction can be calculated though a inversion analysis under the assumption that the faulting is caused by the maximum shearing stress acting on the fault plane. We have determined the principal stress direction and the principal stress ratio normalized by minimum principal stress. Figure 3 shows the region of principal stress directions. Even though it is impossible to determine a unique solution, the possible directions of principal stress can be calculated. The principal stress directions shown in figure 3 is considered to represent the stress field at the depth of about 1050 m since the sources of the multiplets are located around the depth. We have also calculated the principal stress ratio. The estimate of the stress ratio is given as a function of the pore-pressure at the target depth. When the pore-pressure around the structural planes is equivalent to hydrostatic pressure, the ratio of σ_1/σ_3 and σ_2/σ_3 are estimated to be 2.22 and 1.10, respectively. The horizontal stress direction were also evaluated from the experiment using boring core at the depth of 919m (Kondo 1994). It is reported that the maximum horizontal stress direction is N29° W, and that the stress ratio σ_H/σ_h is 2.41. Since we can consider that the multiplets are the events representing the regional subsurface condition, the structural planes and the stress field determined using multiplets can be suggested to be representing the regional stress.

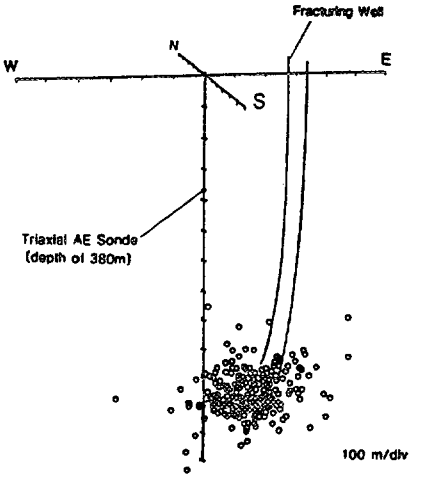

Fig.1 Absolute source locations.

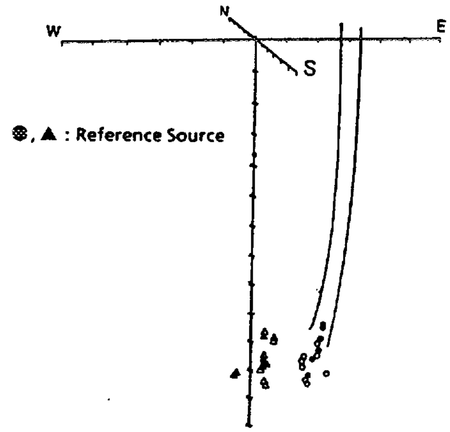

Fig. 2 Relative source locations (doublets and multiplets).

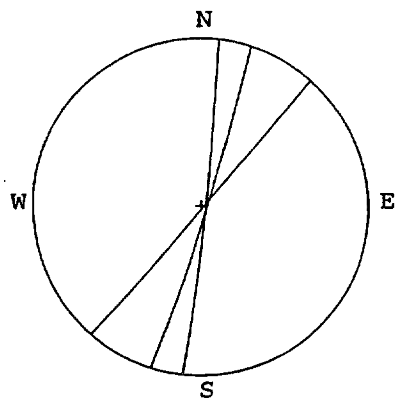

Fig.3 Structural planes defined from the hypocenters of multiplet.

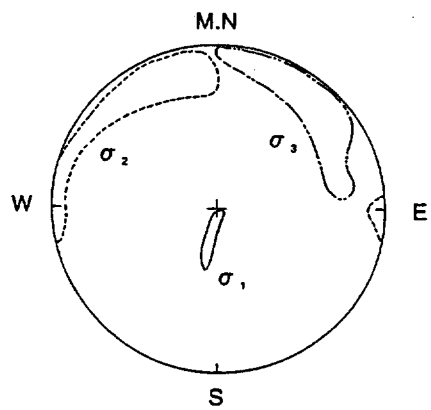

Fig.4 Principal stress directions determined using multiplet.

Acknowledgement- This work was carried out as a part of international collaborative research project, MTC -project (MTC:More Than Cloud).

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Kondo, H. 1994. CRIEPI research report: U93039.

3rd International HDR Forum, Santa Fe, New Mexico USA
May 13-16, 1996

Title: The strange case of the Ogachi Reservoir Stimulations

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Two similar stimulations of the HDR reservoir at the experimental site at Ogachi, Akita Prefecture, northern Honshu, Japan (operated by CRIEPI) were carried out in 1991 and 1992. These stimulations were initiated from short open hole lengths, approximately 300m apart at depths of 995m and 715m respectively. The stimulations were monitored by an AE network which provided seismic locations for approximately 1700 events from the first stimulation and 1000 events from the second stimulation. The two AE clouds, each approximately 1000m x 400m in plan view, have possible spatial overlap near the injection borehole, but diverge in the far field. The first cloud extends to the north and north-east whilst that from the second stimulation extends east-west. There is some evidence that the dominant natural fracture orientations at the two stimulation points are different. This paper presents the results of an investigation of reservoir growth direction at Ogachi using a new model of HDR stimulation, which examines whether or not the divergent AE cloud directions can be explained by differing natural fracture directions and minor stress variation about an orientation broadly consistent with what is known of stresses at the Ogachi site.

Model description

A new model of HDR stimulation and circulation has been developed at Tohoku University. The model considers a horizontal section through a 2-D array of steeply dipping natural fractures. The fracture lengths are fractally distributed between lower and upper bounds. Up to 5 joint sets may be specified by azimuth ranges and relative frequencies. Fracture density is determined by field data from core or borehole images. The initial fracture apertures, calculated so as to result in a given initial network permeability, are individually proportional to an initial fracture offset modified by the resolved in-situ effective stresses acting normal to each fracture.

Stimulation is modelled as a quasi-steady state process in which an area of high fluid pressure and large fracture apertures migrates outwards from the injection well at rates determined by the permeability tensor developed inside the high pressure region. Permeability is increased in the stimulated area temporarily through fracture normal compliance at positive (compressive) net effective stress, and through jacking when the fluid pressure exceeds the normal rock stress. A largely non-reversible increase in permeability is achieved by associated sliding of the fractures with progressive mismatch of opposing faces with offset. The amount of opening and sliding are approximately calculated using simple equations for the shear stiffness and jacking stiffness of circular disks [*Jaeger and Cook*, 1969; *Dieterich* 1992] and by treating the whole reservoir itself as an ellipsoidally expanding region. This allows an approximate estimate of the totality of crack interactions as a 'backstress' or resistance to crack opening in the stimulated area. Details of crack slip from which the post-stimulation aperture can be derived using a simple constitutive law [*Hicks et al.*, 1996] are carried forward into the circulation calculation.

Flow through the fracture network is modelled by mapping the fracture traces onto a fine grained finite difference grid, in this case 200 x 200 elements, each cell 8 metres square. Steady state fluid flow with fracture apertures opening in response to the local fluid pressure is calculated, but there is no attempt at estimating any stress re-distribution as a result of circulation injection pressures. Boundary impedances which are a function of the boundary pressure simulate flow to the far field through compliant fractures. Injection and recovery wells are modelled as constant pressure cells.

Having established the steady state flow, heat may be extracted under the assumption that fluid and rock temperatures in each cell are instantaneously at equilibrium. This simplifying assumption is found to be sustainable for typical HDR circulation flow rates and finite difference cells of the sizes up to 10 metres or so that are typically used to discretise the fracture network.

A more complete description of this model is available in *Willis-Richards et al.* [1996].

Seismic Imaging of Stimulation at Ogachi

Two stimulations were carried out from the same hole in 1991 and 1992 respectively. In 1991 the open hole section was 10m in length at a depth of 995m; 10,164m^3 of water were injected at a near-steady well head pressure of about 18.5 MPa through 76mm casing at an injection flow rate of 620 - 720 litres/minute. In 1992 a casing reamer was deployed to open a short length of casing at 715m and the bottom of the hole was isolated by sand. 5,400m^3 of water were injected at well head pressures of 18 to 22 MPa and flow rates of 400 - 700 litres/minute. No estimates of friction losses or near well bore pressure drops are available, so the effective formation treatment pressures remain uncertain.

1738 induced seismic events were located during the first stimulation using P-wave arrivals at up to 8 observation stations, although most locations utilized only 4 or 5 timings. During the second stimulation 1088 events were located, mostly using 6 or 7 timings. Details of the data acquisition, signal conditioning and the acoustic emission locations have been published by *Kaieda et al.* [1993]. The first stimulation produced an AE cloud some 1000m x 500m x 200m elongated towards the N and NNE with some evidence of a vertical planar structure. The second stimulation produced a slightly smaller cloud of some 800m x 400m x 200m extending to the east and slightly downwards from the injection point. The two seismic clouds appear to overlap slightly near the injection well.

Fractures and Stress at Ogachi

The direction of maximum horizontal stress has been estimated using the Kaiser effect (AE emission onset on recompression) on cores from a depth of 900m, by *Kanagawa et al.* [1981], reported as N127°E by *Kaieda et al.* [1993], and as N151°E by *Kondo* [1993] working from the same data. Kaiser effect stress estimates remain experimental, and were not utilized by the World Stress Map [*Zoback*, 1992]. The map shows a regionally consistent maximum horizontal stress direction for northern Honshu of about N110°E to N120°E based on Quaternary volcanic alignments and overcoring. Differential strain curve analysis has been applied to core from well HDR-3 at the Hijiori HDR project not far from the Ogachi site [*Oikawa et al.*, 1993]: five out of eight samples showed the maximum principal stress direction to be E-W or ESE-WNW.

BHTV oriented cores were recovered from the open hole section chosen for the 1992 stimulation [*Kondo*, 1993]. Most fractures are steeply dipping with a slight predominance of approximately E-W strikes and southerly dips. BHTV fracture images from 600m to 800m shows no predominant preferred azimuth. In contrast images from 800m to 980m show a dominant N-S fracture trend with easterly dips.

The nature of the problem

Work in Europe, chiefly from the Rosemanowes and Soultz HDR projects had, prior to the publication of the Ogachi results, been slowly arriving at a consensus with respect to the broad interpretation of large scale AE clouds resulting from stimulation:

AE "Euro-consensus"

- The major features of AE clouds can be interpreted in terms of smoothly varying stress fields and the frictional stability of existing natural fractures
- Approximately elliptical large scale AE clouds are common
- The minor axis indicates, approximately, the direction of minimum stress
- The major axes contain, approximately, the maximum and intermediate principal stresses
- Re-inflation of a stimulated region will be generally aseismic until the previous stimulation pressure is reached, after which seismicity recommences, often at the margins of the old AE cloud. (AE Kaiser effect)
- Upward or downward growth from the injection open hole section can be interpreted in terms of the vertical effective stress gradients.
- Growth to one side of the injection open hole section is common: whether this is caused by structural or stress control is unknown.

The Ogachi results challenge this. They show two clouds, with the injection open hole sections close together and with some AE overlap near their origins, progressing in distinctly different directions.

Several possible hypotheses can be suggested to explain the Ogachi results within the context of the European HDR/AE work. These include:

1. Significant stress variation with depth/position at Ogachi
2. Variation in fracture orientation controlling AE growth direction
3. Alteration of the in-situ stress field by the 1991 stimulation re-routing the 1992 stimulation
4. Pervasive non-random errors in the seismic locations for one or both tests

The possible overlap of the AE clouds near their injection points suggest that hypotheses 1 and 2 may not be tenable, but is hardly conclusive. This contribution examines the possible control of stimulation growth direction by preferred natural fracture orientation, while work in progress by Jones et al. at CSM Associates in the UK is providing stringent quality control checks on the location data.

Modelling of Stimulation

A variety of SE quadrant maximum horizontal stress directions and magnitudes were studied, each with a variety of joint azimuth distributions in an attempt to reproduce AE clouds trending NNE-SSW and E-W controlled by variation in fracture azimuths alone. Figures 2 and 3 show results typical of the best achievable results.

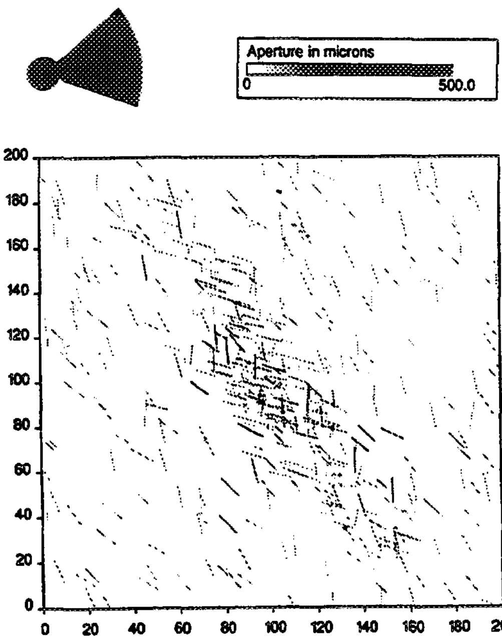

Fig. 1. Fractures with apertures greater than 50μ after stimulation. σ_{Hmax} from 151°, fractures dominantly E-W.

The modelling suggests that even strongly biased fracture orientations can move the direction of stimulation only by up to about 30° away from the maximum horizontal stress direction. Thus the maximum feasible separation of stimulation directions in the same stress field is about 60°. The AE clouds observed at Ogachi are separated by about 120° relative to a maximum horizontal stress from the SE quadrant.

We conclude, based on the modelling performed here, that the variation in AE cloud horizontal growth direction reported from Ogachi is unlikely to be due to changes in fracture azimu-

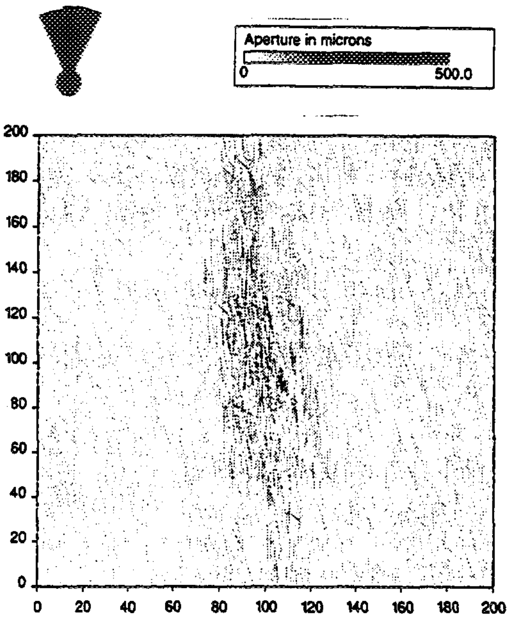

Fig. 2. Fractures with apertures greater than 50μ after stimulation. σ_{Hmax} from 151°, fractures dominantly N-S.

-th alone. We may also conclude that if a variation in the direction of maximum horizontal stress is involved as well, that it must be by at least 60°.

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Three-dimensional Simulation for Ogachi HDR Reservoir

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We made a three dimensional reservoir estimating code, named GEOTH3D. The code is consisted of numerical methods based on three-dimensional finite difference approximations with fully implicit Newton-Raphson treatment of nonlinear terms. The numerical methods are the law of Mass and Momentum Balance under the assumption of Darcy's law for multiphase flow in porous media, and Energy Balance.

The three-dimensional distribution of permeability in the reservoir at the Ogachi site is decided both from the data of acoustic emissions (AE) in micro-earthquakes and the results of hydraulic communication tests. The minimum size of the block used in this calculation is $20 \times 20 \times 20$m, and the block interval is variable.

The initial permeability that measured just before the fracturing (operated in 1991) was 1×10^{-16} m^2, and the permeability measured after the wellbore stimulations (operated in 1994) was 4×10^{-15} m^2. We set the minimum value of permeability as 1×10^{-16} m^2, the maximum one as 1×10^{-14} m^2, and divided the range into five ranks. The minimum cumulated magnitude of AE in a block is -3.7, and the maximum value is -0.1. We set the minimum cumulated magnitude as -4, and the maximum value as -0.1. We also divided the range into five ranks to translate the data of AE into the values of permeability. Fig.1 shows the distribution of permeability in the S-N section, including the wellhead of the injection well.

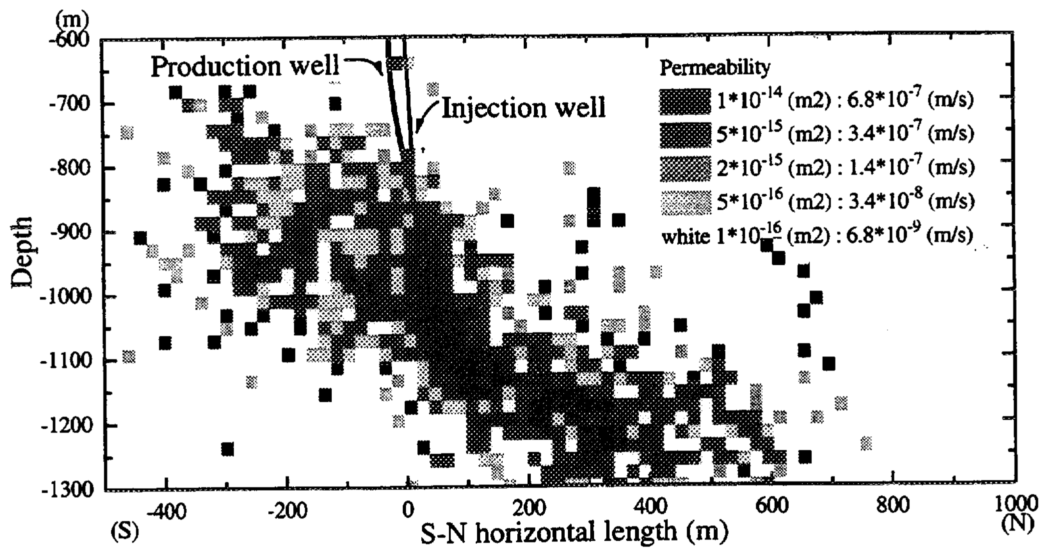

Fig.1 Permeability distribution in the S-N section

Fig.2 shows the flow rate pattern used in the reservoir estimating simulation. The minus value stands for the stimulating injection flow rate, operated before the hydraulic circulation. During this period, the water is set to be injected into the production points, where product the circulating water during hydraulic circulation.

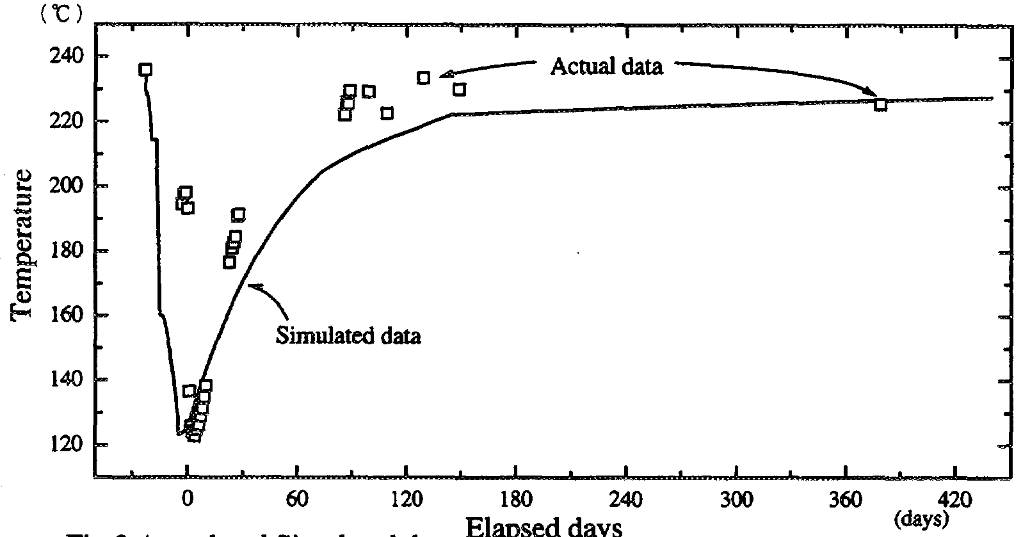

Fig.3 Actual and Simulated data

Fig.3 shows the simulated temperature change and actual one that were observed at 1,060 meter depth in the production well. The simulated data seem rather good. In this simulation, the position of the production points and the flow rate at those points were set as the same as the actual data. The data were logged by a spinner / flowmeter. The total recovery in this simulation was set to 10%, as same as the actual data.

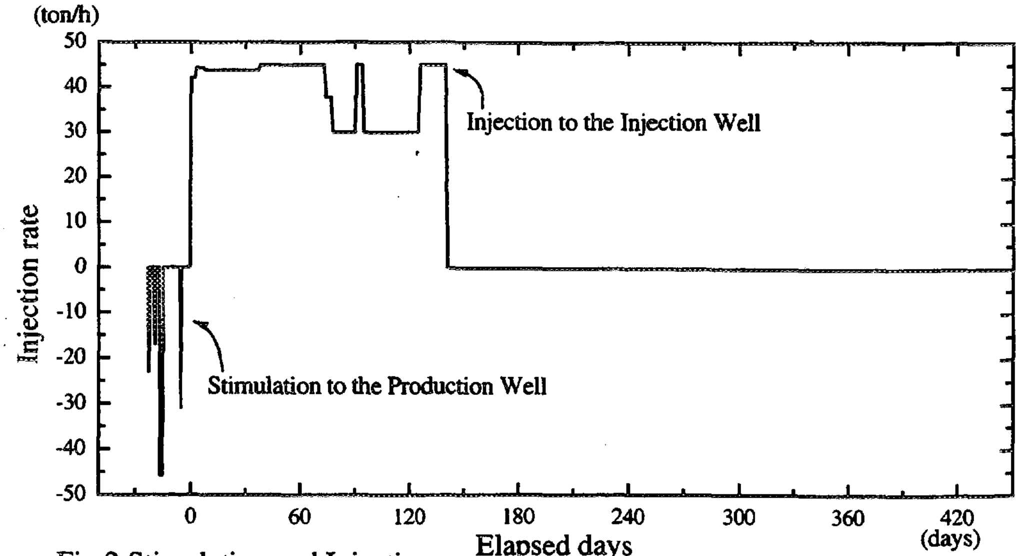

Fig.2 Stimulation and Injection patern

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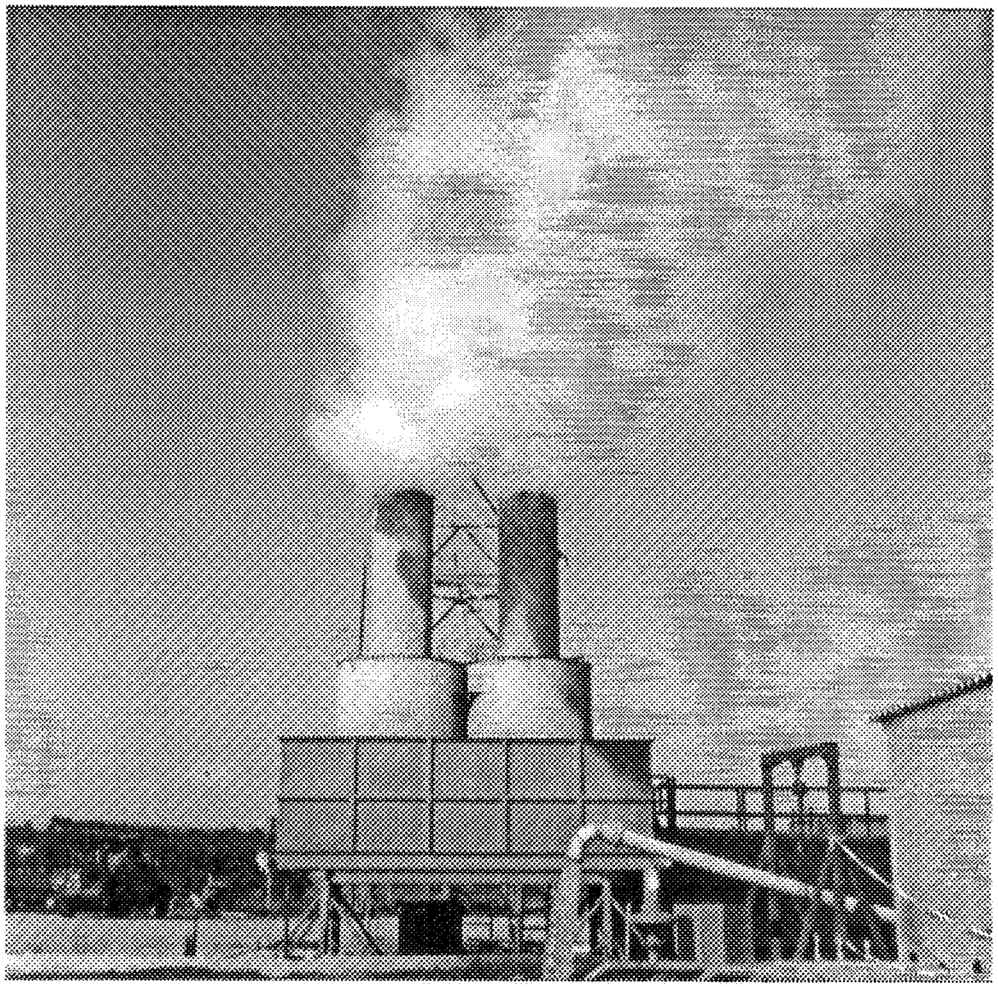

Progress at the European HDR site at Soultz, France

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The development of HDR technology to exploit deep geothermal resources in Europe has been concentrated at the single research site in France. The site is situated about 50 km north of Strasbourg in the Rhine Graben, which extends over 300 km.

The site possesses two deep wells and four shallow wells. The deep wells are GPK1 and GPK2, which are drilled to 3590 m and 3876 m depth respectively. The separation between the two wells is about 450 m. The temperature gradient is high at around 100°C/km in the upper 1000 m but declines in the granite and then increases again at depth. The temperature in GPK2 is 168°C at 3800 m depth, 76 m above the bottom of the well. The shallow wells vary in depth from 1400 m to 2200 m and are used as seismic observation wells and deep piezometers.

Core samples and geophysical logs show that the granite in this basement is highly fractured and contains swarms of joints/faults which are altered by hydrothermal action. Observation suggests that there are two principal joint sets striking N10E and N170E and dipping 65°W and 70°E respectively. Hydrofracture stress measurements suggest that S_H is very close to S_V at around 3000 m depth ; S_h is very low and close to the hydrostatic pressure, which would indicate that it would be relatively easy to inject fluid into the granite basement. The direction of S_H is about N 170° E. There is some natural production from both wells and the in-situ fluid is saline with a salinity of about 100 g/l.

Large scale hydraulic injection using fresh water was carried out in the first deep well in 1993; the majority of the fluid left the well in the top part of the open hole at around 2850 m depth. The exchanger grew mainly by shear mechanism. The maximum overpressure reached was in the order of 10 MPa. Microseismic monitoring showed that the predominant growth direction was NNW-SSE and there was some tendency to migrate upward forming a stimulated rock volume of about 240×10^6 m^3.

A second deep well, GPK2, was targeted some 450 m to the south of GPK1 near the edge of the microseismic cloud. The well was completed to 3876 m. GPK2 was stimulated in a similar manner to GPK1 but using 300 m^3 of heavy brine pad (1.18 g/cm^3) followed by natural brine produced from GPK1 (1.06 g/cm^3). This was done in order to increase the pressure gradient in the well, to reduce the effect of the in situ stress gradient and so to try to achieve a more balanced depth distribution of flow outlets from the well. Flow logs performed during injection showed that this technique was highly successful. Furthermore, seismic monitoring confirmed that the heavy brine assisted in the creation of a connection to the deepest part of the existing stimulated structure around GPK1 (Fig. 1). Overall, the hydraulic stimulation improved the injectivity of the openhole section of GPK2 for low flowrates by a factor of 20, from around 0.5 l/s/MPa to around 10 l/s/MPa. An immediate and distinct hydraulic pressure response was observed in GPK1 due to the injection in GPK2.

During various circulation tests, which included the use of a submersible pump in GPK1, it became apparent that the use of a submersible pump in a relatively open media was crucial to the maximum recovery of energy. Using a downhole pump in GPK1, a circulation rate of more than 21l/s was obtained while injecting the same flow into GPK2. The surface temperature of the brine produced approached 136°C, delivering at the surface a thermal energy output in the range of 8-9 MW (Fig. 2) before reinjecting at 40°C.

No tracer was recovered during the 6 weeks of circulation tests indicating either that the reservoir was very large or a possible absorption or degradation problem occurred. A dramatic increase of the hydraulic injectivity, the successful use of a downhole pump to enhance recovery without pinch off effect, relatively low pressures required to circulate and a virtually equilibrated water balance suggest that future development of an HDR type of technology can successfully be targeted at an area similar to a Graben structure or on the margins of existing hydrothermal system. In these environments higher temperatures usually can be encountered at shallow depths, relatively low minimum stress gradients are observed and the likely hood of finding open joints/faults (natural permeability) at depth is large. The concept of working in a Graben setting is meanwhile also known as the "Soultz" concept in Europe, but similar working concepts are have also been developed in Japan. It should be mentioned, however, that multiple wells systems will almost certainly be necessary in such settings if water losses are to be kept to reasonable proportions.

The research carried out in Europe has demonstrated again the importance of a well developed understanding of the interaction between in-situ stresses and the joint network for the enhancement of the injectivity & productivity of an initially poor productive formation. The experience in Europe to date suggests that HDR research is more likely to meet the technical targets and then the economic targets if further research in the development of this type of technology is - for the time being - approached from a Graben setting. Another obvious advantage with this approach is that some of the technologies developed can be transferred immediately to existing hydrothermal industries and thus gain their interest in the development of this new technology.

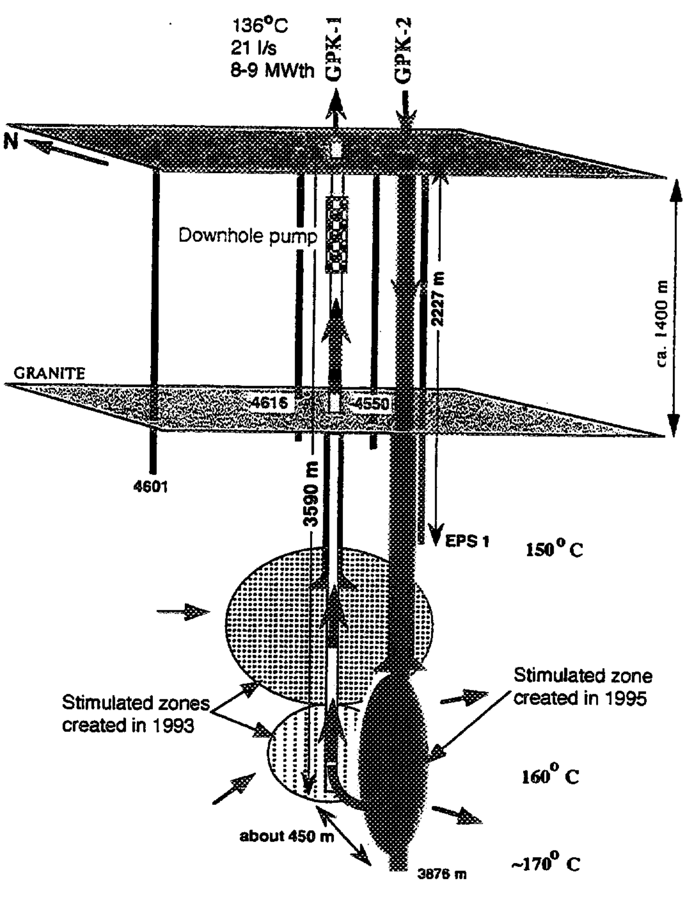

Fig. 1. Schematic view of the system created at Soultz

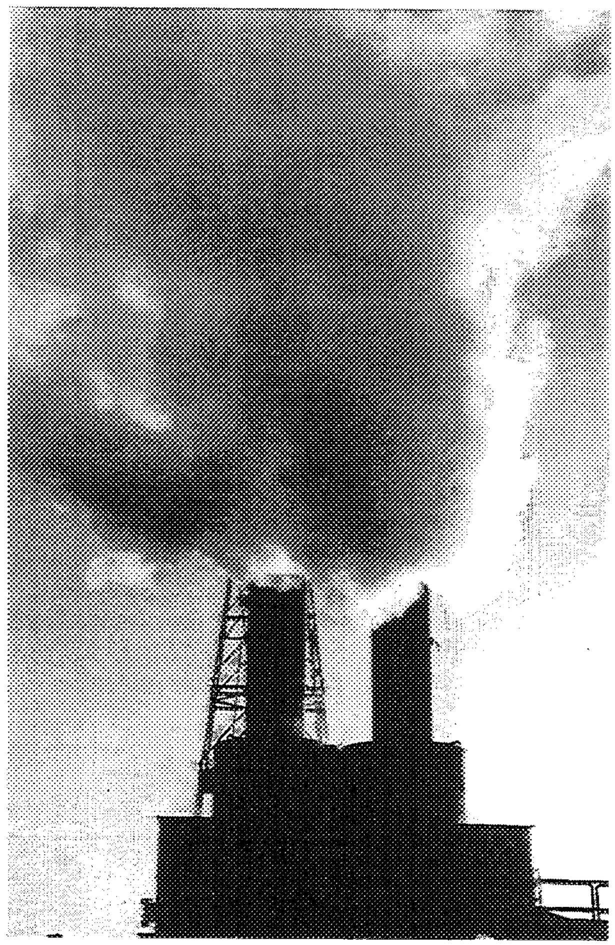

Fig. 2. Circulation at 21 l/s (335 GPM) using an E.N.E.L separator

Large Scale Hydraulic Injections in the Granitic Basement in the European HDR Programme at Soultz, France

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An extensive hydraulic programme had been performed in the Soultz HDR-project during the last 4 years. The tests were performed in the depth range between 2800 m and 3900 m in the two boreholes GPK1 (3590 m) and GPK2 (3870 m) forming now a doublet with a borehole to borehole distance of 450 m.

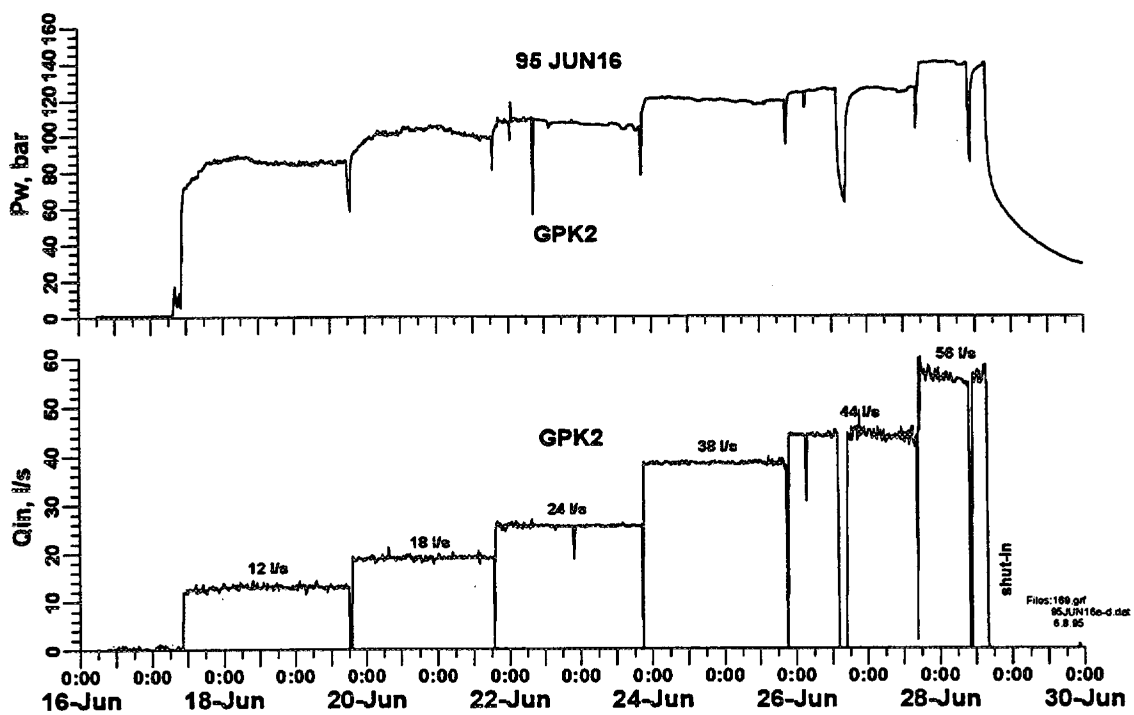

Fig.1: Records of the injection flowrate and the wellhead pressure of stimulation test 95JUN16

Two large NNW - SSE striking overlapping and interacting fracture systems had been stimulated by injecting 45.000 m^3 (GPK1) and 28.000 m^3 (GPK2) of freshwater or brine at flowrates up to 56 l/s and over-pressures up to 120 bar (Fig.1).

The distibution of micro-seimic events and of the flow exits in the boreholes proofed that upward or downward fracture growth can be controlled to a certain degree by the density of the fluid used for stimulation.

Post-fracturing hydraulic testing showed that the hydraulic conductivity of the stimulated fracture systems at hydrostatic or sub-hydrostatic pressure is sufficiently high to achieve production or injection flowrates in excess of 20 l/s even though the flow conditions proofed to be turbulent at flowrates above 6 l/s (Fig.2).

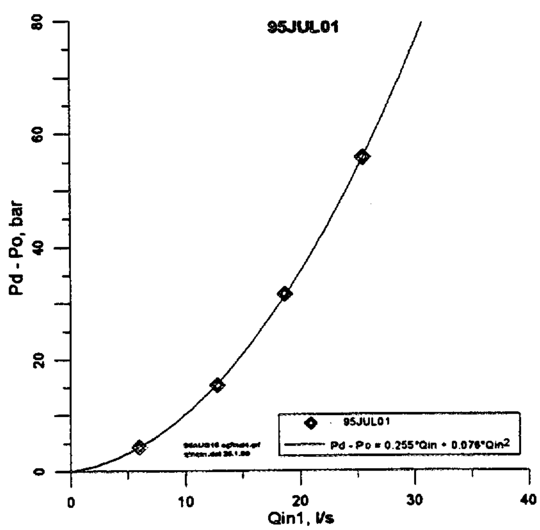

Fig. 2: Steady state pressure difference versus injection flowrate during a post-fracturing step-injection test in borehole GPK2.

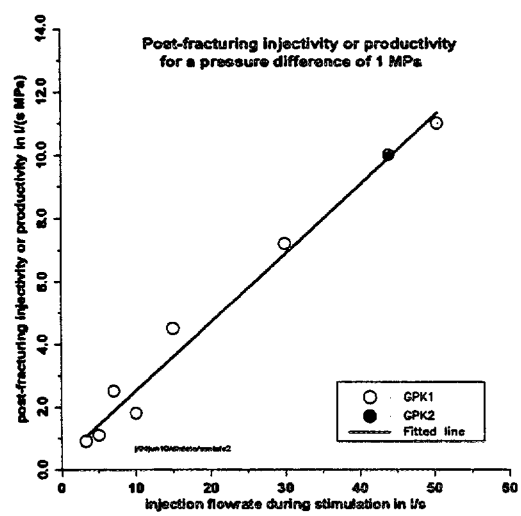

Fig. 3: Post-fracturing injectivity or productivity of all stimulated fractures in boreholes GPK1 & GPK2.

Both fracture systems seem to be limited by constant pressure boundaries (probably faults) acting as sinks or sources during hydraulic testing or circulation. The productivity or injectivity resulting from the connection to these boundaries was linearly related to the flowrate applied during stimulation (Fig. 3). Short term circulation tests between the two wells demonstrated that downhole pumping in one of the wells in combination with reinjection in the other well is a suitable mean to operate a HDR-system in the presence of such open boundaries. It could be shown that flowrates of more than 20 l/s can be maintained in that way over an extended time period. It was also demonstrated that reinjection improved the production flow significantly and was essential for preventing a continuous decline of the production flow observed previously for pure production.

HYDRAULIC STRESS MEASUREMENTS AT THE EUROPEAN HDR TEST SITE SOULTZ - SOUS - FORETS

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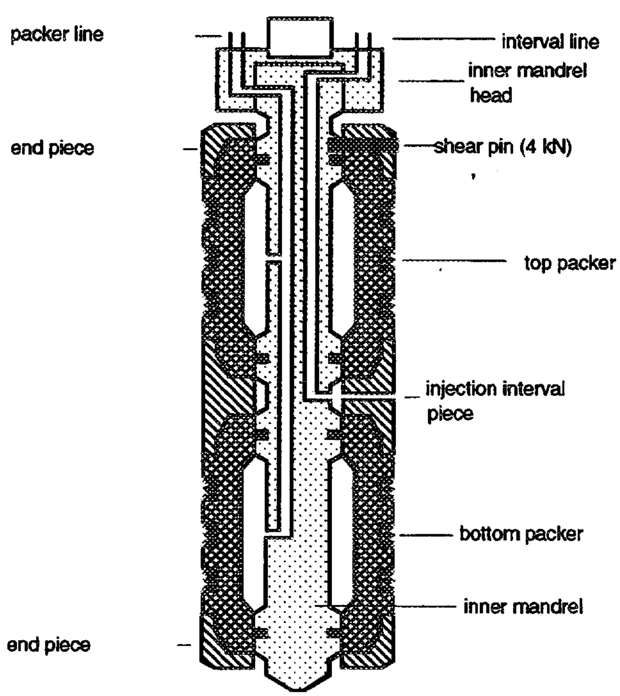
Costs of long-term HDR system operation are determined by the energy demand for underground fluid circulation as well as by fluid losses during circulation. Both factors are controlled by in-situ stresses at depth. Therefore in-situ stress measurements as part of feasibility studies at HDR locations have high priority.

Although sophisticated packer technology (high pressure, high temperature packers) exists, conventional hydrofrac testing at great depth often encounters a number of problems such as high pressure to seal borehole sections, or high temperature and high gas content of the borehole fluids. These will result in failure of the packer elements and may cause severe problems to the borehole. Therefore the determination of in-situ stresses at reservoir depth at the European HDR research test-site Soultz-sous-Forets required the development of new packer elements as part of a wireline hydrofrac system. Major components of the aluminum straddle packer tool (Fig. 1) are two soft aluminum packer elements connected to high strength aluminum end-pieces and an injection interval piece, and an inner steel mandrel with deep borings as hydraulic connections to the packer inflation sections and the injection interval.

Fig. 1:Schematic diagram of an aluminum straddle packer system



Prior to in-situ hydrofrac testing, prototype aluminum packers were investigated in a high pressure / high temperature borehole simulation autoclave system, which was developed to permit testing of newly designed logging tools under controlled laboratory conditions. The tests demonstrated that the aluminum packer unit can be operated at pressures up to 100 MPa under hostile HDR downhole conditions. Presently, the new packer technology is considered to be used for permanent borehole sealing at nuclear waste disposal sites.

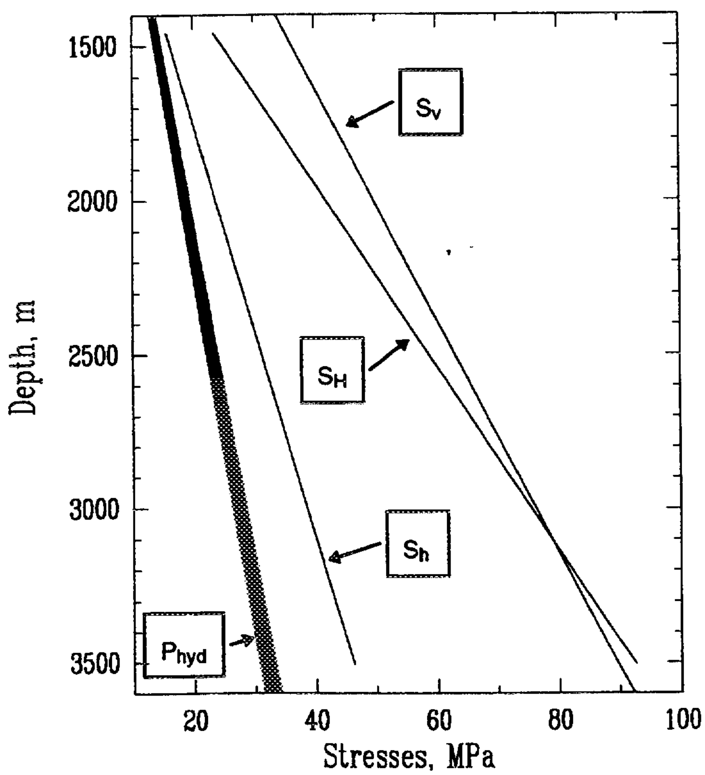
After laboratory testing, the aluminum straddle packer arrangement was successfully used down to 3.5 km depth (temperature up to 170 °C) in the Soultz boreholes GPK-1 and EPS-1. Summarizing the hydrofrac test data available, the following stress - depth relations were obtained:

S_h, MPa = 15.7 + 0.0149 · (z, m - 1458 m)
S_H, MPa = 23.5 + 0.0337 · (z, m - 1458 m)
S_v, MPa = 33.1 + 0.0261 · (z, m - 1377 m) for ρ = 2.66 g/cm^3 in the granite

where $S_{h,H}$ are the minor and major horizontal principle stresses, S_v is the vertical stress due to the weight of the overburden with given rock density (Fig. 2). The derived orientation of the maximum horizontal compression θ (S_H) is N 155° ± 3° for the depth range between 1458 m and 2000 m and N 170° ± 10° for the depth range between 2000 m and 3300 m.

These data suggest a normal to strike - slip faulting stress regime ($S_h < S_H \leq S_v$), which agrees with the tectonic situation in the Upper Rhine Graben and therefore offers favorable conditions for hydraulic circulation experiments.

Fig. 2: Stress - depth profile at the HDR test-site Soultz-sous-Forets.



The observed orientation of the acting major horizontal stress of N - S to NNW - SSE is in accordance with the existing stress orientation in Central Europe. However, HDR development at greater depth requires deeper stress testing at temperatures of about 200 °C. Improvements of the existing aluminum packer technology to meet future demands are being developed.

Multiscale organisation of fractures in the HDR Soultz granite reservoir from core and borehole-imaging data

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The fracture system of the HDR Soultz granite reservoir located in the Rhinegraben (France) was analyzed in three deep wells (EPS1, GPK1, and GPK2 see Fig.1). The study of the density and spatial orientation of fractures was based on coring and high-resolution borehole imaging techniques, including BHTV, FMS, FMI, ARI, and UBI. At macroscopic scale, the comparison between the fracture population depicted from cores and those interpreted from borehole images allowed us to improve the interpretation of the different borehole images in terms of fracture typology. At large scale, the organisation of fault zones was also investigated in order to propose some guidelines for build up a 3-D geometrical model of the HDR reservoir.

Fracture system in the EPS1 well (1420-2230 m depth)

An exhaustive analysis of several thousand of macroscopic fractures cut by the EPS1 well was made on a continuous core section over a depth interval from 1420 to 2230 m (Genter and Traineau, 1996). 97% of the structures were successfully reorientated with a good degree of confidence by comparison between core and oriented BHTV data. The fracture population is organised in clusters and grouped in two principal fracture sets striking N005 and N170, and dipping 70°W and 70°E, respectively. This organisation is related to the rifting activity of the Rhine graben during the Tertiary (Dezayes et al., 1995). Only 1% of the fractures show a significant free aperture whereas the others are completely sealed by hydrothermal products.

Only 500 fractures were sampled by the BHTV, compared to 3000 fractures observed on cores. Due to its spatial resolution, the BHTV was not able to detect fractures thinner than 1mm and representing 75% of the whole population on cores. Furthermore, the BHTV was not able to properly characterize too closely-spaced fractures, and thus their clustered organization observed on core sections. Nevertheless, the spatial orientation of fractures was correctly sampled since the BHTV distinguished the two main fracture sets.

Fracture system in the GPK1 well (1376-3600 m depth)

In the uncored GPK1 well, the fracture system was only investigated by means of different electrical (FMS, FMI, ARI) and acoustic (BHTV) imagery techniques (Genter et al., 1995; Tenzer, 1995) from 1376 to 3600m depth. Two contrasting borehole sections were evidenced in terms of fracture density: an upper, highly fractured section from 1376 to 2000m characterised by a major N160-N170 set, and a deeper, poorly fractured section from 2000 to 3600m, characterised by a major N020 set. Moreover, in the deeper section (2900-3500m), the low spatial resolution ARI tool which detects the most conductive fractures, preferentially sampled fractures striking N020 and N150 which are considered to be the most relevant structures for fluid circulation for HDR reservoir development.

Fracture system in the GPK2 well (1425-3880 m depth)

A high resolution borehole imaging system (UBI) was run over the whole granitic section of the GPK2 well, providing fully oriented images of the borehole wall (Genter and Tenzer, 1995). About 1800 natural fractures were identified between 1425 and 3800m depth. The major nearly-vertical fracture set, which is conjugated, is striking N175 and dipping 70°W and 70°E. A main opened fault located at 2115m, which caused total losses during drilling, is oriented N150 and dipping 75° E.

Fractured and hydrothermally altered zones in the Soultz granite

The results obtained in the three boreholes show that natural fractures are organized into clusters within the granite defining highly fractured zones. These zones enabled past fluid circulation which resulted in significant hydrothermal alteration characterized by the deposition of clay minerals mainly. Thirty nine, twelve, and 52 fractured zones were cut in the GPK1, EPS1 and GPK2 wells, respectively. Their true width ranges from 0.1 to 28m with an average value around 2 m. In the three wells, they are mainly oriented N160. Some of these fractured and altered zones still carry hydrothermal brines and develop a naturally-permeable network within the Soultz granite. Differences exist in the orientation of these permeable altered zones: NS oriented and dipping West in EPS1 (2175m depth) and GPK1 (3490m depth); N120 oriented and dipping North in GPK1 (1815m depth); and N150 oriented and dipping East in GPK2 (2115 and 3245m depth). Schematic vertical cross-sections through the EPS1, GPK2 and GPK1 wells show that the fractured zones are not randomly distributed along the vertical. They are concentrated in two main zones in the EPS1 and GPK2 wells, and in three main zones in GPK1 well. These concentrations of fractured zones can represent major faults in the granite basement showing a quite regular spacing between 300 and 400m. Although a lot of assumptions exist concerning the 3-D extension of these fault zones, the next step will be to build up a 3-D deterministic geometric model of the fault network, in order to predict the connection between the HDR geothermal doublet at the scale of the reservoir.

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The Analysis and Interpretation of Microseismicity Induced during the 1995 Stimulation and Circulation Experiments at the European HDR Project at Soultz-sous-Forêts, France.

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In the framework of the European Hot Dry Rock Soultz Project, a second deep borehole, GPK2, was completed in 1995 to a depth of 3.8 km. This new borehole is sited at about 400m southward of the existing GPK1 borehole which reaches a depth of 3.6 km. During the summer 1995, a programme including hydraulic stimulations of GPK2 and circulation between both boreholes was carried out. In order to monitor the microseismicity induced during this programme, the three 4-axis accelerometers sondes deployed in 1993 at depths around 1500 m in peripherical boreholes for previous hydraulic tests were still operational; to complement this network, a hydrophone probe was also deployed in borehole EPS1 at 2170 m depth.

Stimulation experiments

After an aseismic pre-stimulation period of GPK2 at low flowrates with GPK1 formation fluid and an overpressure of 3 MPa, the main stimulation hydraulic experiments started on 13th of June to 29 th. During the first 2 day-long test, heavy brines and GPK1 formation fluid was injected in GPK2 (GPK1 remained shut in) at flowrates steps of 0.5 l/s and 30 l/s; when the overpressure rises rapidly to 12 MPa, seismicity activity becomes intense with an average event rate of 2 events per minute. More than 500 events are located closely around GPK2 suggesting that the region of high pressure has not travelled far from the borehole source. The next stimulation experiment lasts 11 days with a 6 l/s step by step increased rate of injection from 12 l/s to 44 l/s, and a final injection rate of 56 l/s. GPK1 borehole is allowed to produce (apart from the 44 l/s flowrate) and formation fluid mixed with fresh water is injected. The onset of microseismic activity occurs at an overpressure of around 4.5 MPa, consistent with the observations during 1993 (GPK1 stimulation) and 1994 programmes. Clear correlations are observed between the steps in the event rate and the steps in the GPK2 wellhead pressure associated with increasing injection flow rates. Around 6000 events are located during this period. These events form a cloud of approximately 800 m horizontal elongation orientated NW/SE to N/S and approximately 800 m vertical extent. The microseismic cloud is shown in figure 1 (borehole trajectories are surimposed upon the clouds for clarity), where it is compared with that from the 1993 GPK1 stimulation. Two directions were identified in the microseismicity: at the bottom hole a more N/S alignement was observed; at shallower depths, the events aligne with the jointing in a NW/SE direction. During the first three injection phases, the microseismic events are largerly separated from that produced during the 1993 GPK1 stimulation. Later on, the event locations begin to encroach into the 1993 GPK1 microseismic cloud. Moreover, it is interesting to note that growth occurs either side of the 1993 locations, leaving an aseismic zone around GPK1: this may represent a shadow zone caused by the low hydrostatic pressure due to outlow of this borehole. This suggests that the drawdown of GPK1 during production may hinder the hydraulic connection between GPK2 and GPK1.

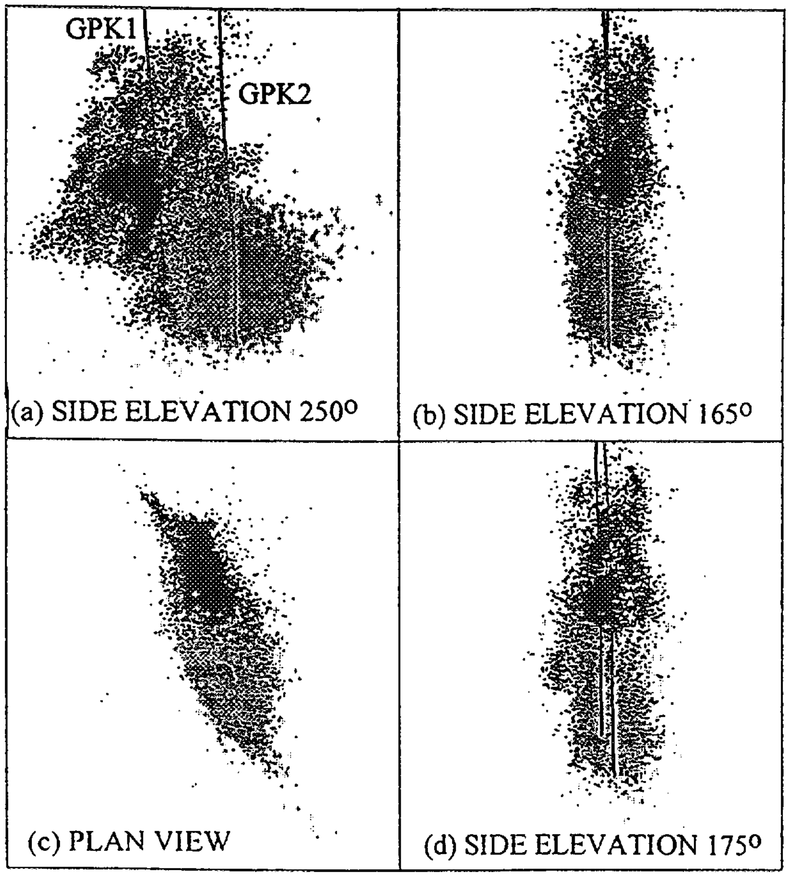

Figure 1 : Microseismic event locations from the 2 nd stimulation test of GPK2 (shown in grey) and the 1993 stimulation of GPK1 (shown in black).

Circulation experiments

During the circulation experiment between GPK1 and GPK2, 2 phases are undertaken: the first one using the natural buoyancy method, and the second one using a downhole pump in the production well GPK1. During the first test which lasts 17 days, flowrate injections in GPK2 starts at 15 l/s and then was increased later to 22 l/s, reaching an overpressure of about 5 MPa. As expected, the microseismic event rate was much reduced (30 located events) due to the low overpressures and scattered across the stimulated zone. For the second test which lasts 11 days, a pump intake is positioned at a depth of 383 m. Injection rate into GPK2 starts at 20 l/s, reaching an overpressure of around 5 MPa. The well head overpressure at GPK1 is maintained at 1 MPa during this experiment: as a result the seismicity around GPK1 is much reduced and only 3 located are detected.

GEOCHEMICAL MONITORING OF INJECTION TESTS AT SOULTZ GEOTHERMAL SITE

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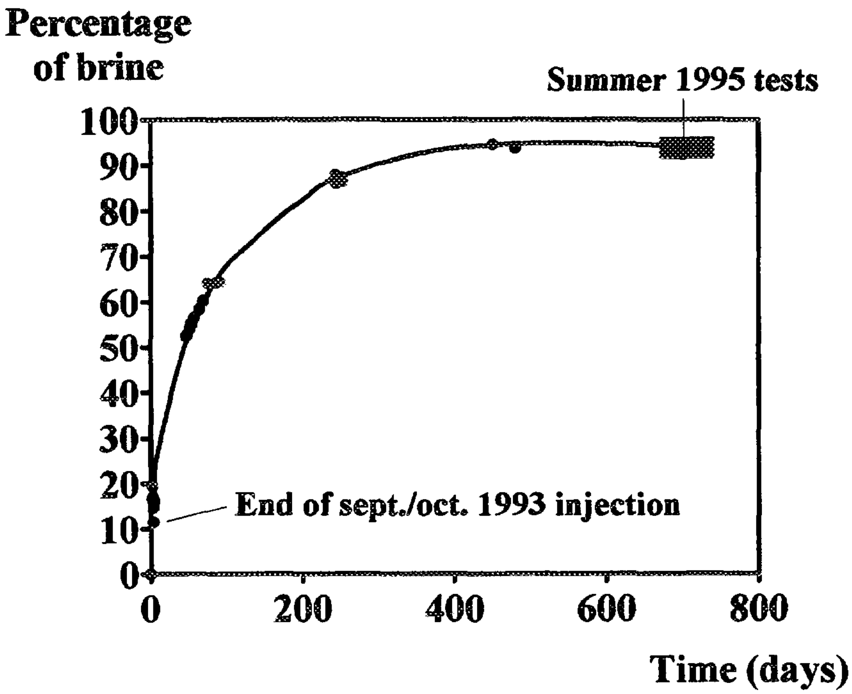
The geothermal site of Soultz-sous-Forêts is the french site of the European Hot Dry Rock project. The aim of the project is to create a heat exchanger in granite which constitutes the basement of the Rhine graben. Large fracture zones, some of which carry natural brines have been encountered in the granite at depths of 1800 to 3800 m. These fracture and the natural brines of the granite make the Soultz site original for the H.D.R. concept. In 1993 several experiments of injection and production have been carried out in order to determine the hydraulic properties of the granite in the GPK-1 borehole, at a depth of 2850 to 3500 m. In the 1995 summer, injection and circulation tests have been carried out to establish a connection at 3500 m depth between the GPK-1 and GPK-2 boreholes.

Hydraulic fracturing tests of 1993 :

A vertical NW-SE fracture system with a size of more than 1 km^2 could be created during these tests by injecting large quantities of freshwater (45,000 m^3). The results of pre and post-fracturing production and injection tests show that the productivity and injectivity of the well increased by a factor of 20 due to the fracturing tests to an extent that longterm production flowrates of economical interest (20 l/s) can be achieved. It is concluded that the stimulated fracture system is connected to a natural geothermal reservoir existing in the cristalline basement.

Chemical analyses of the fluid produced before and after the injections have allowed the computation of the chemical geothermometry of the natural fluids and of the percentage of deep formation brines produced after the injection of fresh water. These results indicate that the natural fluids which circulate in the granite have encountered temperatures above 230°C. The chemistry of the fluids produced after injection show that the 45,000 m^3 injected in september and october have been absorbed by the fracture network. These results are in good agreement with hydraulic observations and confirm that the fracture network is connected to a large hot geothermal reservoir at a temperature of 230-250°C.

The evolution of the percentage of brines contained in the fluids produced by GPK-1 during 1994 and 1995 is shown in the figure. It can be seen that just after the injection, the increase of natural fluids is nearly instantaneous. During the first monthes it is still extremelly rapid. After several monthes, it stabilizes and after nearly two years, no increase can be determined. This curve indicates that the injection of fresh water has created a strong desequilibrium of the system. The reaction is very rapid and implies fluid velocities of several km/yr. Aftewards, the system tends to its natural equilibrium and the velocities can no more be measured at the scale of two years.



Injection and circulation tests of 1995 :

The fracturing tests have been carried out in the GPK-2 borehole in order to establish a connection with the 1993-stimulated GPK-1 borehole. About 50,000 m^3 of fluids have been injected in GPK-2 and a similar volume has been produced by GPK-1. A fluorescent dye (Fluorescein) pulse has been added to the injected fluids. During the tests, the chemical composition of the injected and produced fluids has been monitored.

During the fracturing of GPK-2, the down-hole pressure record of GPK-1 showed a clear increase. After the fracturing test, the natural productivity of GPK-1 was enhanced from 13 l/s to more than 20 l/s, which demonstrate that the two boreholes have been hydrolically connected.

The composition of the fluids produced was slightly different between the fracturing tests and during the circulation tests which followed. This indicates that a different area of the natural fracture reservoir was stimulated.

The tracer injected in GPK-2 was not recovered in GPK-1, although 50,000 m^3 had been produced during more than 20 days production. No decrease of the Ca and Cl concentration was noticed, although very large volumes of fresh water had been injected in GPK-2. This result implies either that the tracer and the fresh water have been completely diluted by the natural brines, which is quite unlikely. It is thought that the fluids produced by GPK-1 originate from the vicinity of this borehole and have been pushed by the fluids from GPK-2 which had no time to reach GPK-1. Independantly of the solution, this result allows to compute that the volume of the granitic reservoir is 200 m high, 450 m length and about 50 m thick. It also indicates taht the size of the heat-exchanger is more than 3 km^2.

MODELLING NON-LINEAR FLOW TRANSIENTS IN FRACTURED ROCK MASSES

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During the Hot Dry Rock (HDR) site investigation studies in Soultz s.F. (France) several stepwise hydraulic injection and production tests have been conducted in the two boreholes GPK1 and GPK2 in 1994 and 1995. At near steady state conditions the two 1994 tests 94JUN16 and 94JUL01 in GPK1 showed clearly that changes in flow rate invoke parabolic changes in pressure which indicates non-laminar hydraulic behavior. Conventional hydrological models assuming Darcy flow along fractures only can describe linear pressure changes with flow rate. Another feature of non-laminar flow is nicely highlighted by the 1995 injection test 95JUL01 in GPK2: an increase of the transient phase with increasing flow rate. This feature is also not explainable by simple Darcy flow assumptions.

With the special purpose to investigate non-laminar flow in fractures the 3-D finite element code FRACTure has been extended. Our interpretation is based upon constitutive flow laws derived from various laboratory fracture flow measurements. Assuming 2-D models of simple geometry with non-laminar flow in fractures and sublaminar flow in the bulk rock results in an excellent match of the transient pressure records (see Fig. 1 and Fig. 2 for the 1994 and 1995 multi rate injection tests). The model results demonstrate particularly that turbulent-like hydraulic regimes can easily be establish in fractured media and may extend over large fracture surfaces even at moderate flow rates. The existence of high capacity far-field faults as postulated in our model is consistent with earlier characterisations of the Soultz test site.

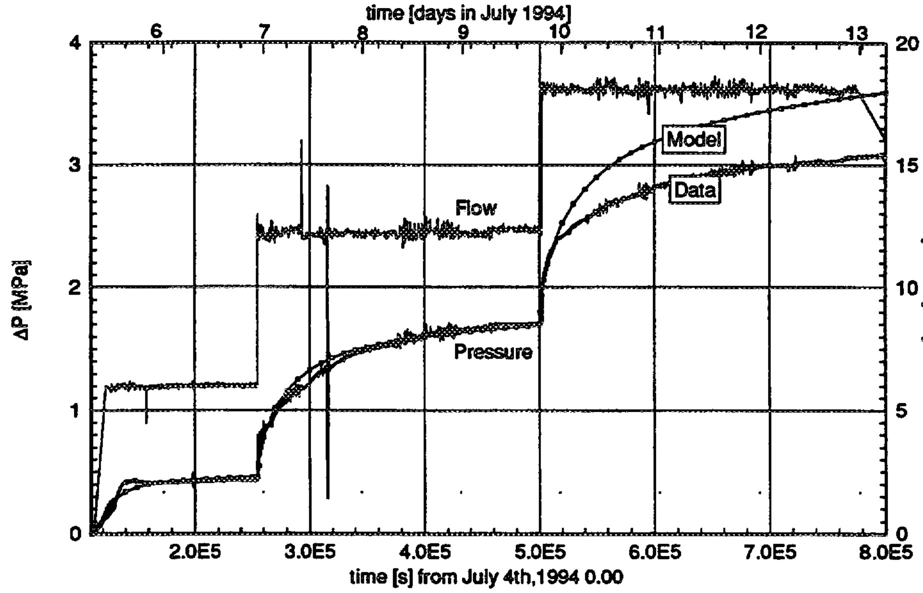

Fig. 1: Record of flow rate (stable-steps) and downhole differential pressure during the injection test 94JUL04. The best-fit model prediction is shown by the circled line.

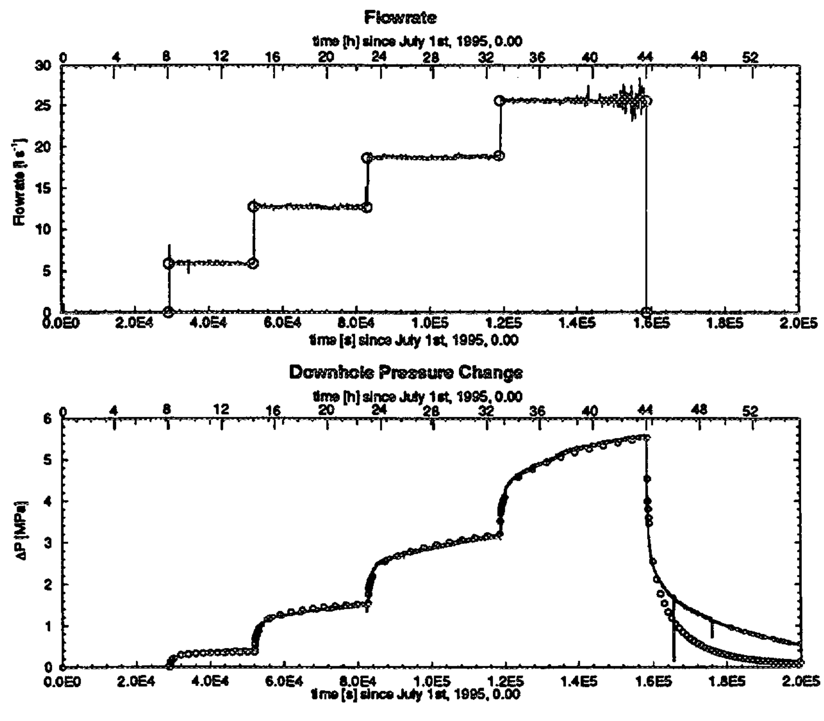

Fig. 2: Fit of the measured pressure record of 95JUL01. The hollow symbols on the pressure record indicate the numerical results, on the flow data they indicate points of a stepwise linear interpolation function.

Hydraulic response of the Soultz rock mass to GPK1 injection and production tests: Analysis of individual flow zones

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Earlier studies of GPK1 hydraulic behaviour during injection and production tests have revealed that jacking occurs at a surface injection pressure of about 10 MPa, and that the differential pressure required to drive flow varies as the square of flow rate at sub-jacking pressures. The latter implies that non-linear, turbulent-like flow was occurring somewhere within the conduits that feed the well. Both observations were demonstrated by plotting steady-state wellhead flow against the corresponding differential pressure at the casing shoe. The conclusions thus reflect the behaviour of the dominant flow zone which was the 80 m section below the casing shoe that accounted for ~60% of flow. In this study we perform a similar Q-P analysis on deeper flow zones to clarify the evolution of the transmissivity of each zone during the stimulation process, and establish whether non-linear flow also occurs at zones other than the dominant one.

For the analysis the open hole section of GPK1 was partitioned into six zones and several sub-zones, each of which typically contained a flow point (Figure 1). The flow entering or leaving each zone at a particular steady-state pressure level was then estimated from the appropriate flow profile. The latter was obtained by correcting the spinner log for cross sectional area variations and depth errors. The results are shown in Figure 2 and indicate:

1) Progressive increases in the transmissivity of all zones took place during the stimulations which are best explained by extensive shearing within the rock mass.

2) Significant transmissivity increases occurred in most flow zones during the microseismically-quiet period <u>between</u> the September and October 1993 stimulations. The effect is not confined to the primary flow zone immediately below the casing shoe but is manifest down to at least 3250m. The observation suggests that significant aseismic shearing took place during this time.

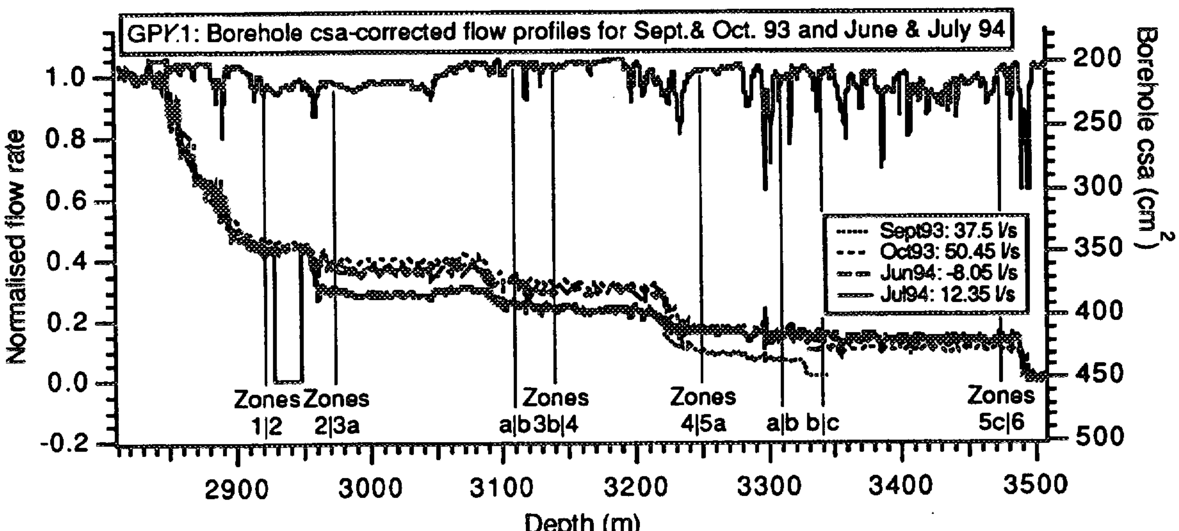

Figure 1 Examples of normalised corrected flow profiles taken from each GPK1 test. The logs are normalised to unity at the casing shoe. The marked change in flow path that occurred at some time between the last log of the June and the first log of July is evident.

3) Non-Darcy flow characterised all zones: even where the flow contribution was less that 0.5 l/s. For the shallowest and the deepest zones (the latter contains a prominent fault) the flow contribution demonstrably varied as the square root of the differential pressure, as expected for turbulent-like flow. The analysis of the flow regime for the other zones was complicated by a change in flow paths within the formation. However, the flow regimes are clearly non-Darcy.

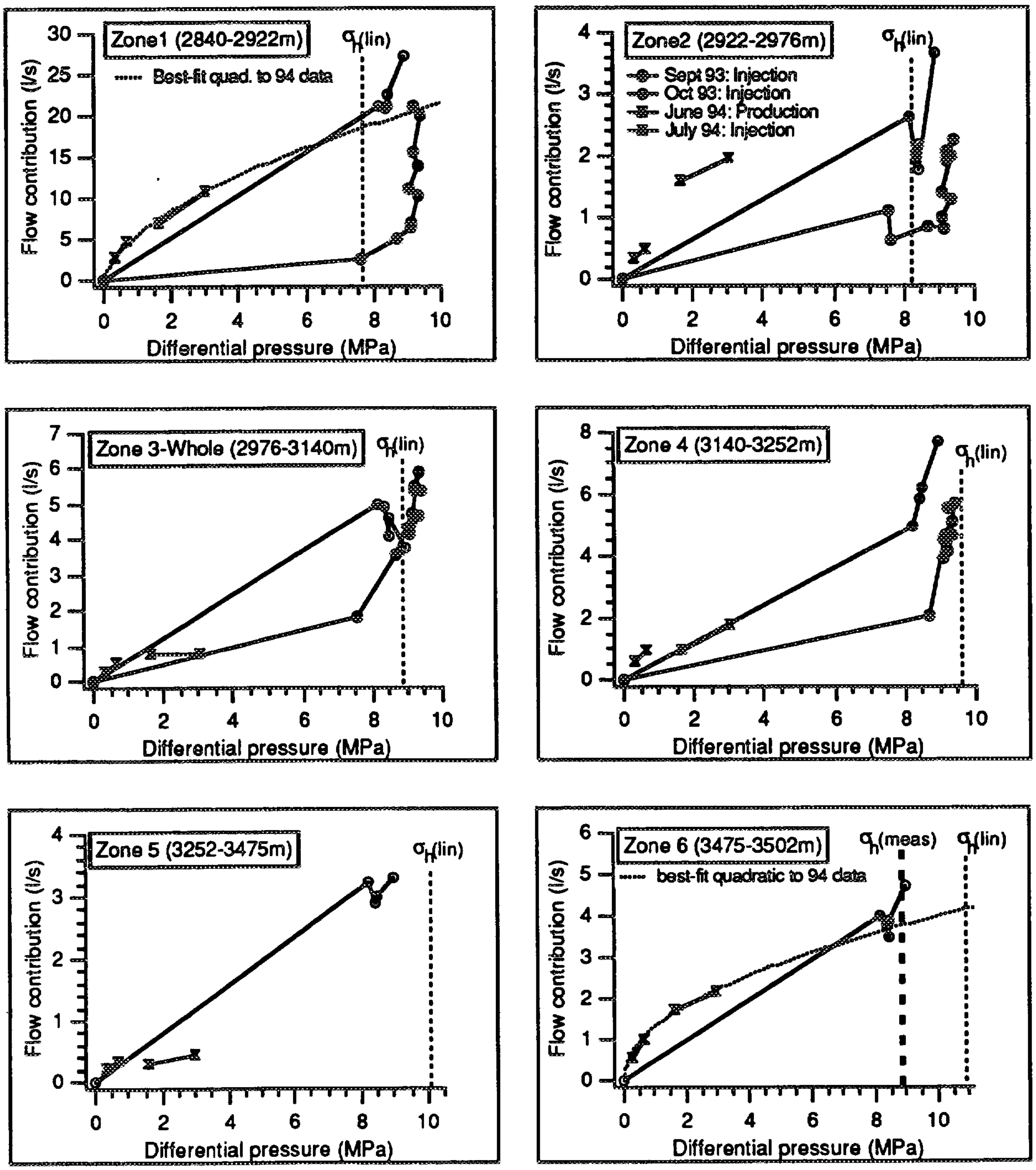

Figure 2 Steady-state ΔP versus ΔQ cross-plots for each zone shown in Figure 1. The data are from the 1993 September and October stimulation injections and the 1994 June (production) and July (injection) evaluation tests. All flow rates are plotted positive. Production and injection data points may be considered together provided that flow path geometry is the same and viscosity effects are negligible.

Natural and Induced Seismic Hazards of the European Hot Dry Rock Geothermal Energy Site of Soultz sous Forêts (N.E. France).

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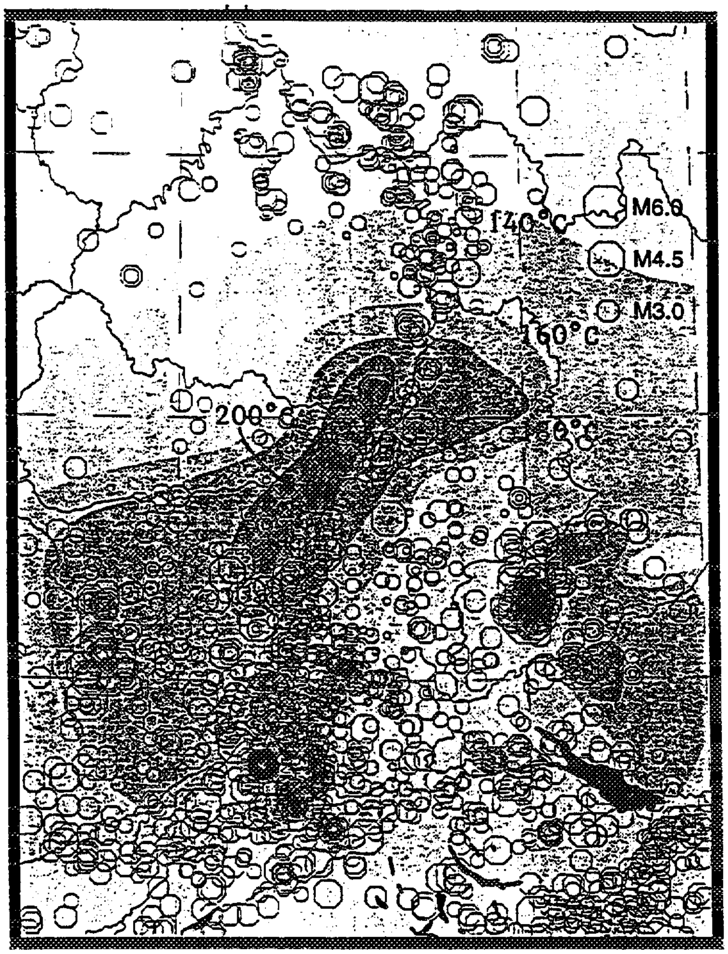
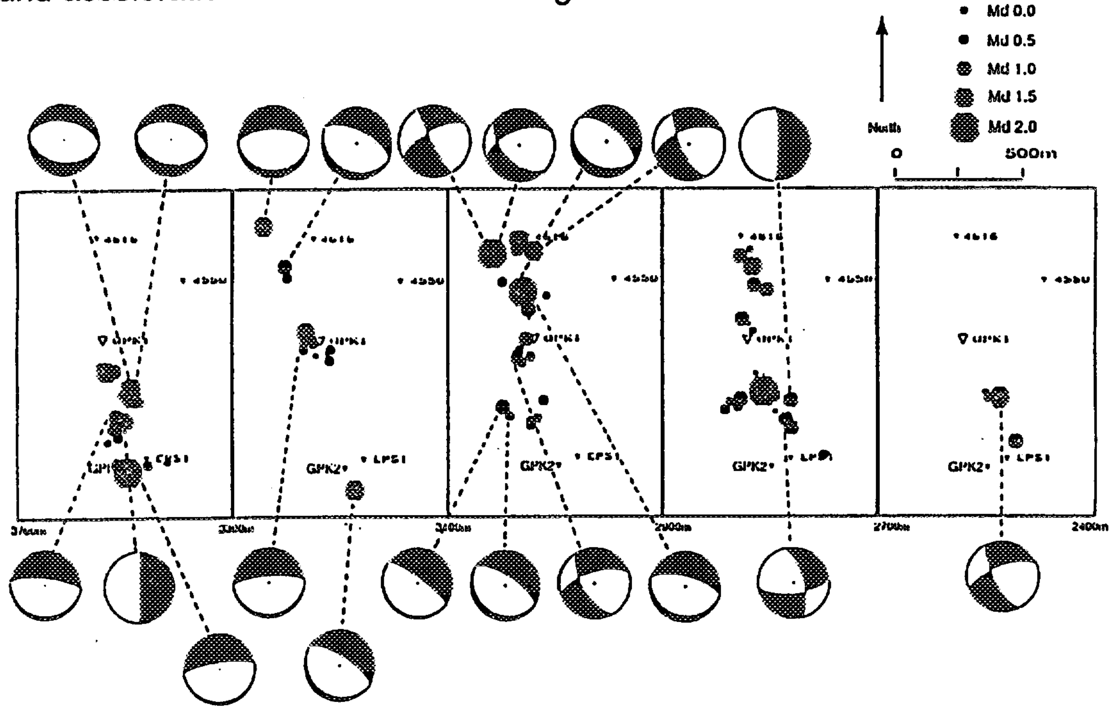
Natural local seismicity is monitored by a permanent 3 - station seismological network composed of both seismometers and accelerometers. Instrumental documents have shown that the geothermal site has an extremely low level of seismic activity in comparison to other regions in the Rhine Graben. This low level appears to correspond to the large heat flow anomaly identified in the region. Furthermore, a M5.8 regional earthquake ($\Delta = 280$ km) implies few influences on the site : the maximum ground acceleration due to this event and recorded at a local station was only 18 mg.



Seismicity and Geothermal Gradient
of the Upper Rhine Graben

Besides the permanent stations, 8 mobile stations grouped in a telemetered network and 3 stand alone 3D stations were set up around the HDR site whilst hydraulic stimulation's took place in a single well (June - July 1991 and August - November 1993). The initial phase of injections has induced micro - earthquakes with magnitude less than - 0.5, too small to be detected by surface instruments. However, in 1993, 167 events with magnitudes ranged from -0.5 to 1.9, were recorded on the surface network. The induced activity began once the pump rate was increased to 12 l/sec and the injection pressure 9 MPa. Initially, a large number of small events took place until the injection pressure stabilized at 10 MPa. Then, the number of events decreased even though the pump rate was increased to 50 l/sec. The maximum peak - peak ground acceleration recorded was 0.85 mg.



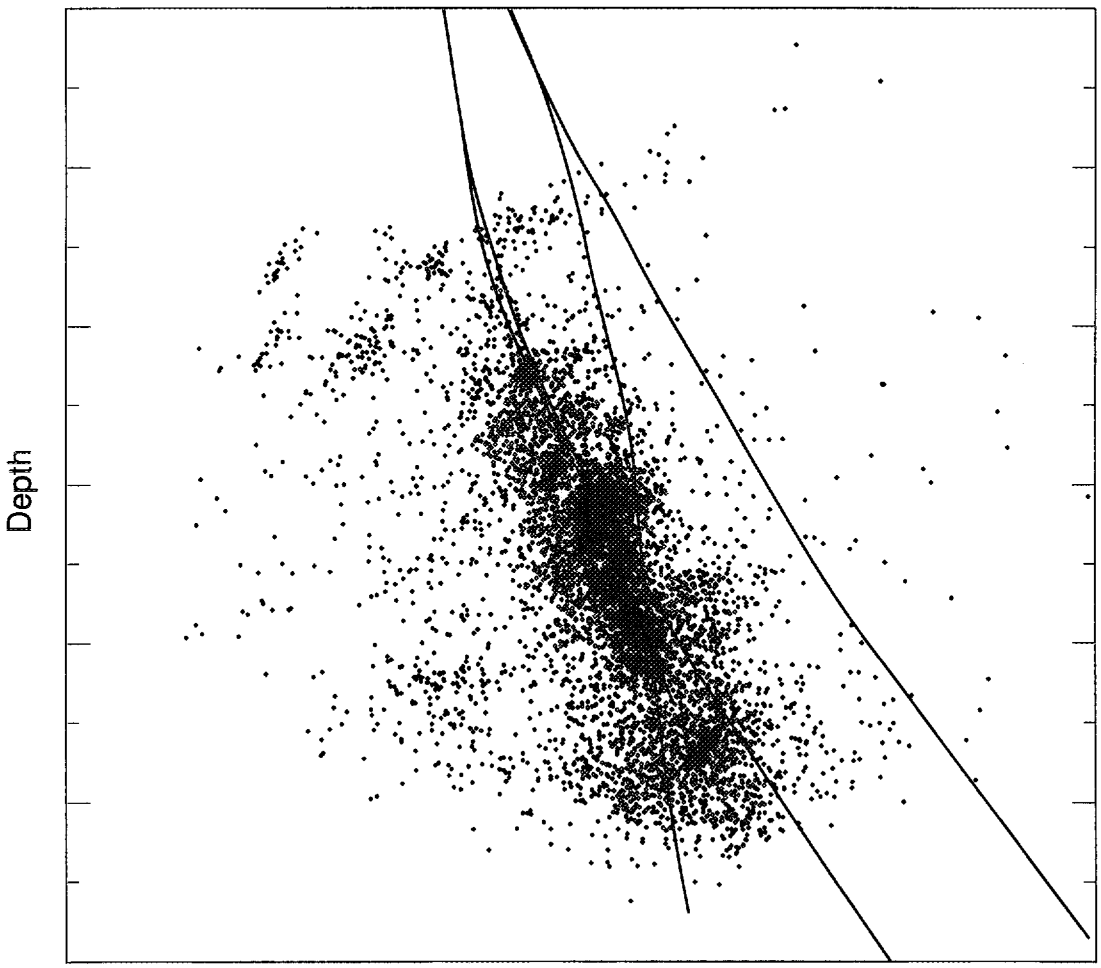
Focal Solutions relative to Induced Events. Each rectangle corresponds to one depth slice

Major events clearly indicate an overall preferential alignment of N155°E. The coefficient b of the Gutenberg-Richter relationship of this induced sequence (b=1.26) is much higher than that of the Rhine Graben (b=0.71). An attempt was made to determine focal mechanisms . This shows that the majority of the shallower events (2000 - 3000 m) are predominantly of strike slip solutions, whilst the deeper ones (3000 - 3700 m) show normal faulting. Stress inversion of the limited data available has given an indication of the direction of the stress field in the region with normal faulting and a maximum horizontal stress S_H direction N140°E.

In conclusion, the natural seismic activity in the region of the Soultz sous Forêts HDR Project is low. On the other hand, injection of fluid can induce a seismicity which until now did not cause any trouble to the environment.

Session 8:
Reservoir Technology

Session Chair: Oscar Kappelmayer



Pressure- Dependent Flow Pattern in a Single Fracture - an In-Situ Experiment

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Introduction

The hydraulic impedance of an HDR reservoir is a function of the driving pressure difference between injection and production wells and reservoir transmissivity. Increasing the reservoir pressure dilates the apertures of reservoir flow paths due to elastic deformation and consequently reduces the flow impedance. It is well-known that the hydraulic properties of the fractures are controlled by large-scale roughness and that flow takes place along tortuous flow channels. It can be expected that the tortuosity decreases and the connectivity of flow paths increases for decreasing effective stress. However, pressure-related changes in the distribution of fracture opening and flow paths within a single fracture plane are poorly understood. To design and to develop an effective HDR reservoir there is a need for increased knowledge of the relationship between effective stress, transmissivity and channeling within single fractures.

The aim of the project is to investigate how the transmissivity distribution and channelling within a fracture will be affected by increases in water pressure.

Site and equipment

The site is situated at the Röda Sten Rock Laboratory in Göteborg at the west coast of Sweden. The laboratory is located 70 metres below surface in a massive granite of Precambrian age. At the laboratory seven vertical boreholes were drilled within an area of 10 m^2. A subhorizontal fracture that within its extension incorporates the boreholes was identified at a depth of about 11 metres beneath the tunnel floor (see figure 1).

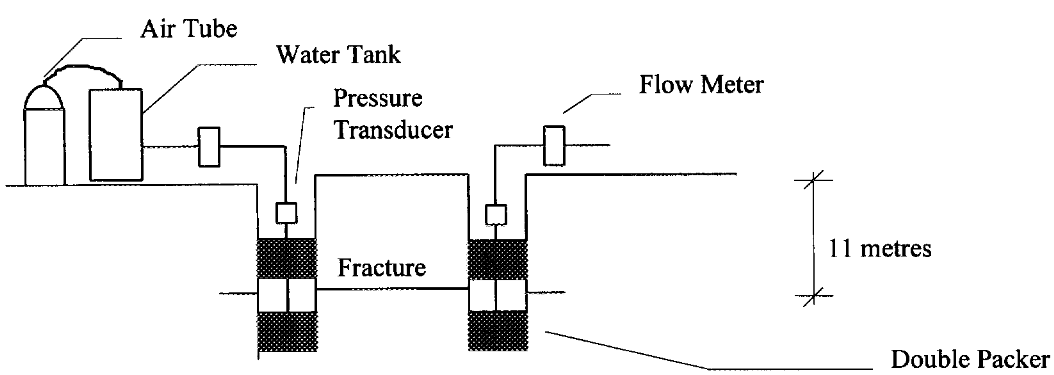

Figure 1. Schematic illustration of test equipment set up.

The fracture is sealed off by double packers in all boreholes. The packed-off sections are 0.2 metres. Close to each packer a pressure transducer is placed and at the surface the flow rate can be measured with flow meter. All pressure transducers and flow meters are connected to a data logger.

Tests and results

The tests started with evaluation of the hydraulic properties and the flow distribution within the fracture under normal conditions (i.e. just above hydrostatic pressure). In order to investigate the outer boundaries of the fracture it was pressurised up to 0,9 MPa and then shut in. The pressure decreased very slowly, from 0,9 MPa to 0,7 MPa within 140 minutes. The results indicate that the fracture has a limited extent and that no major permeable fracture intersects it.

A number of pulse tests have been performed in each borehole in order to investigate the transmissivity close to the boreholes and thereby produce a measure of the transmissivity distribution within the fracture (see figure 2). The results from the pulse tests suggest that one part of the fracture has lower transmissivity than the rest of the fracture. This behaviour was also supported by the flow tests conducted.

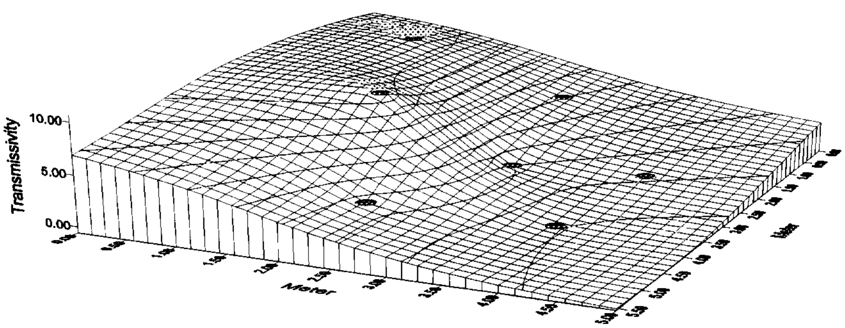

Figure 2. Schematic image of the transmissivity distribution within the fracture as determined from the hydraulic tests. The values on the z-axis shall be multiplied with a factor 10^{-6} m^2/s.

Further work

Following the introductory characterisation phase, the pressure will be increased step-by-step of 0,2 MPa up to the normal stress across the fracture. The hydraulic properties and the flow distribution will be investigated at each step by conducted tracer tests and selected hydraulic tests. Furthermore, the transmissivity distribution evaluated for each pressure level will be compared in order to evaluate the effective stress dependence. The observations in the boreholes will also be used for inverse modelling by simulated annealing.

3rd International HDR Forum
Santa Fee, New Mexico, USA
May 13-16, 1996

Fracture orientation and stress field from borheole measurements and core data of Urach 3 drill hole

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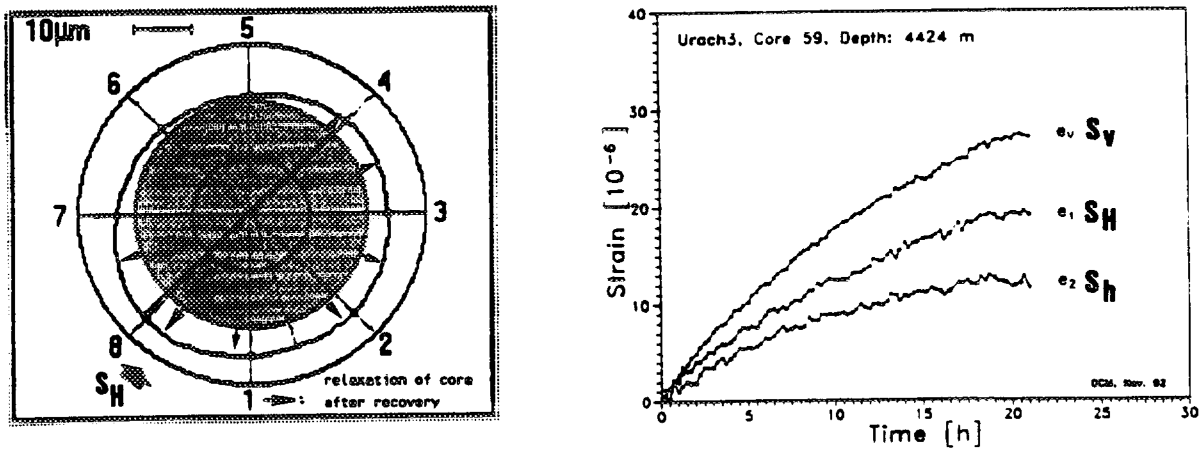
Abstract

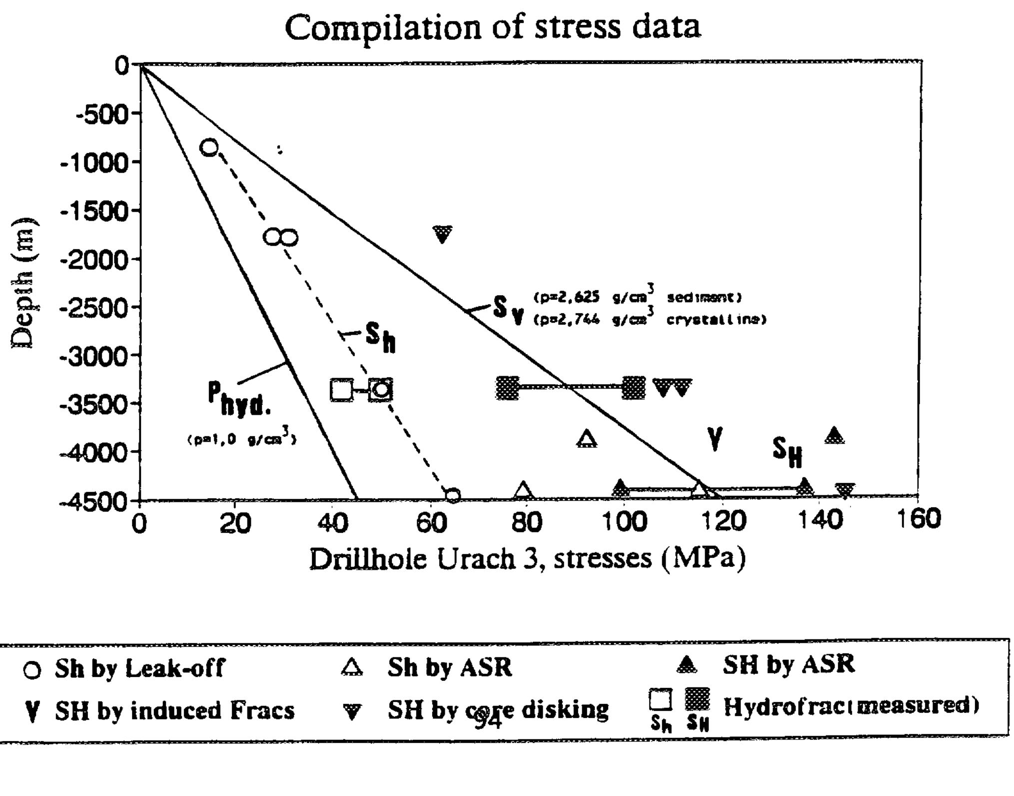
Within the scope of a feasibility study the already existing Hot Dry Rock drill hole Urach 3 was extended from 3488 m to 4440 m depth. Well logging with borehole imagery logs enables continuous recording of natural and artificial planar discontinuities on the drill hole wall and data of the borehole geometry to be measured. Efforts were made to resolve the orientation and characterisation of the natural joint system, the active fault pattern, the alteration zones, the direction of the maximum horizontal stress and the stress profile.
With the help of specific well logs the orientation and frequency of planar discontinuities and their horizontal and vertical persistence can be determined, also their apparent apertures as well as the predominant orientation of the different apertures.
Intense logging programmes and measurements were carried out in the HDR drill hole Urach 3 between 3488 and 444o m depth in the metamorphic gneiss rock of Urach located 35 km south east of Stuttgart in Germany.
The temperature at 4394 m true vertical depth was determined under disturbed conditions at 169°C. It can be proved that the temperature gradient is constant with 2.9 K/100 m depth. Temperatures expected at 4500 m depth are in the range of 172-175°C. As main lithological units biotite-gneiss, anatexite and diatexite were determined. Sillimanite occurs in the metatectic gneiss, with a restitic habit; it means that the gneiss were derived from more or less silicous shales. Anatexis produces segeration of quarzo-feldspathic leucosomes that may mobilised as dykes crosscutting the metatexis. The different cristalline units are effected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulfates) related to former deep hydrothermal circulation. At the bounderies of these fractures the rocks are affected by retrograde processes. On cuttings partly bit metamorphism was effected by drilling determined.

Structural analysis of the joint system by borehole imagery obtains a maximum strike of N 170° E. Orientated drill core were investigated. Three main type of structures observed on core section K 57-60 (14.8.m) are chronologically organised as magmatic foliation, post magmatic vein sealed by early granitic dike, natural fracture and core instabilities. Brittle fracture frequenca per meter in core section 57 (3876-3885 m) and section 59 (4420-4424 m) is about 2 an 8 respectively. On core 57 subvertical sinistral strike-slip shears and faults which correspond to the most intense cataclastic structures occuring in these cores, are striking N 170° E. Features of core disking are striking N 160-170° E and N 10-20° E. On core 59 two main orientations were determined N

100° E and N 30° E with submaxima at N 70° E and N 120° E. Core instabilities show a preferential fracture set which is striking N 10-20 E with a secondary fracture set striking N 120° E.
Hydrofrac packer tests at 3352 m depth yield stress values of S_h=41-50 MPa and of S_H=76-102 MPa. Estimated stress magnitudes of Anelastic Strain Recovery (ASR) measurements on cores from 4424 and 4426 m depth yields values of S_H between 99±2 and 137±8 MPa.
Extrapolation of hydraulic leak-off tests leads to an estimated S_h arround 65 MPa at 4420 m depth. The major horizontal stress direction was determined by different methods (borehole breakouts, Hydrofracs, core disking, and ASR measurements) to be between N 157° E ±20° and N 194° E ±18°.
The stress regime in the Urach gneiss is characterised by a nearly left lateral strike-slip faulting regime with the maximum principle stress having NNW-SSE direction. Due to the results of the investigations it is proposed that the Urach site is suitable for a industrial HDR demomnstration project. The HDR technology can here be followed in the wide spread tectonic horizontal strike-slip system. Many potential consumers of geothermal energy and electricity produced by the HDR concept are situated close arround the Urach 3 drill site.



Anelastic Strain Recovery



The Distribution of Fluid Flow within HDR Reservoirs and the Significance for Thermal Performance

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The distribution of flow within an HDR reservoir controls the thermal performance. The aim is to achieve an even sweep through a large number of fractures within a large volume of rock. In practice the flow is a series of meandering channels in a number of fractures that connect the wells.

The only method available for measuring flow distribution is by the use of tracers. Normally tracer data is presented as a plot of produced volume against tracer concentration. After normalisation several parameters, theoretical and empirical, can be estimated (Figure 1). The analysis of the variation of these parameters with time has been used to assess the evolution of HDR reservoirs.

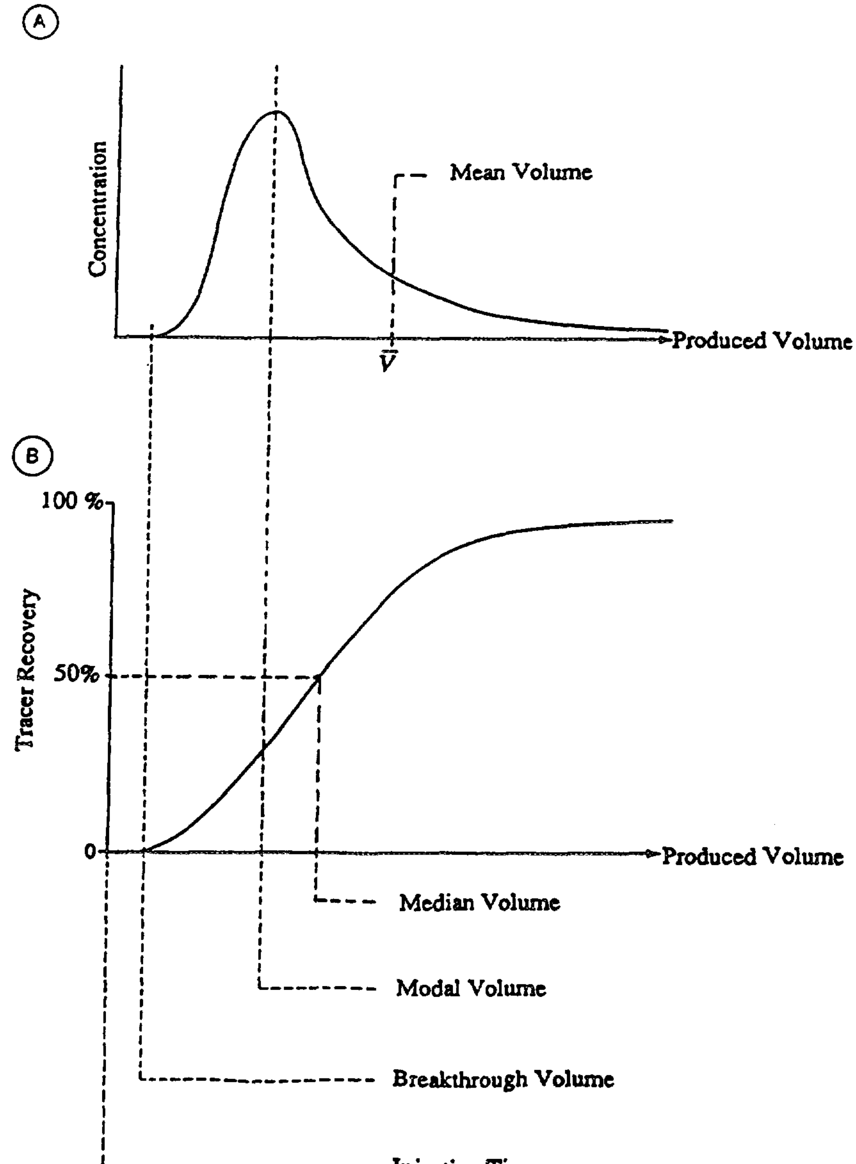
However an alternative is to plot F(t), the external residence time distribution function against X(t), the internal residence time distribution function (see annex). F(t) relates to the fluid flow fraction with a residence time smaller than time t and X(t) relates to the fraction of the volume swept by that fluid. Figure 2 displays data from tracer tests carried out at Rosemanowes (November 1988) and Fenton Hill (May 1992). It shows that at Rosemanowes 60% of the fluid flow is through only 6% of the mean volume while at Fenton Hill 60% of the fluid flow is through 18% of the mean volume. From the point of view of heat extraction the Fenton Hill reservoir is more efficient. The curve corresponding to an ideal parallel plug flow (straight line) is shown for comparison.

The repeated use of tracer tests makes it possible to monitor changes in flow distribution. Figure 3 shows a similar plot for the three initial tracer tests carried out at Fenton Hill during the long term flow test (LTFT) in 1992. In the first two tests, for about 50% of the tracer recovered, about 12% of the reservoir had been flushed whilst during the last test about 15% of the reservoir volume was flushed thus showing an increased sweep efficiency with time. From May to July the mean volume had increased from

The analysis of both figures 2 and 3 also suggests that there is no such thing as an even distribution of flow in HDR reservoirs and that most of the fluid flows through a small fraction of the volume open to fluid flow. As a result the use of parameters for the assessment of HDR reservoirs which have significant contribution from zones where fluid is moving slowly might be misleading. This is the case of the mean volume. A better option involves the use of empirical parameters like the volume of fluid produced until recovery of x% of tracer, $V_{x\%}$, with the values corrected for the transit in the wells. These parameters are less dependant of the effects of slow

moving paths and, in addition, they don't require the estimation of the tail of a tracer curve. If a single parameter is required we advocate the use of the median volume ($V_{50\%}$).
For a larger number of tests a different approach is preferred. In figure 4 $V_{5\%}$ and $V_{65\%}$ are normalised against a particular tracer test (TT13) and then plotted against time, using data from Rosemanowes. This plot covers 5 years of circulation and it includes a number of different experiments. The general trend shows a larger increase in the volume of longer residence time flow paths. This can be seen in the figure by comparing the evolution of $V_{5\%}$ and $V_{65\%}$. The value of $V_{5\%}$ relates to the short residence time flow paths while $V_{65\%}$ is influenced by the long residence time flow paths. The graph also suggests that initially the evolution was faster in the short time flow paths but after about a year of circulation they stabilised. Longer residence time flow paths grew continuously throughout the circulation period shown.

The analysis of the data allows the following conclusions:
i) tracer tests show effectively the evolution of HDR reservoirs;
ii) efficiency of sweep at Fenton Hill and Rosemanowes increses with time;
iii) during long term circulation it is possible for HDR reservoirs to grow in favour of long residence time flow paths. This is contrary to the conventional wisdom which suggests that short residence time flow paths, short circuits, will take more fluid as the reservoirs cools due to thermo-elastic effects.



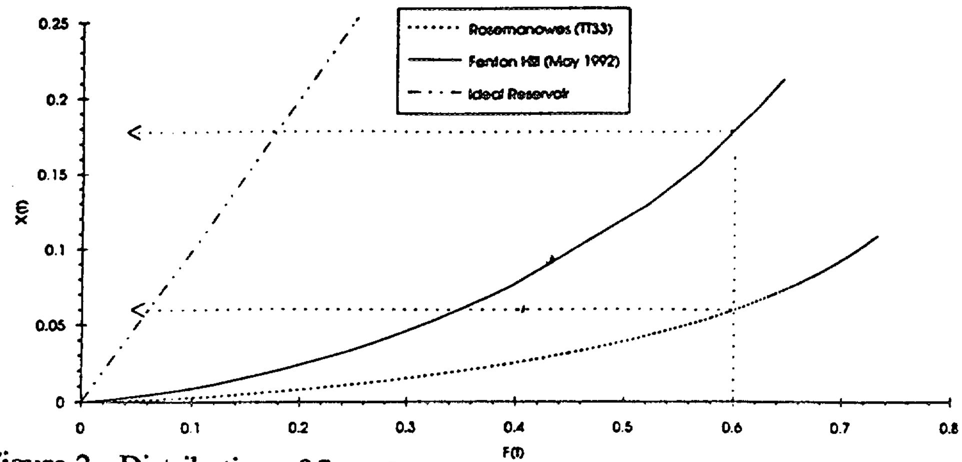


Figure 2 - Distribution of flow: Rosemanowes (TT33) and Fenton Hill (May 1992).

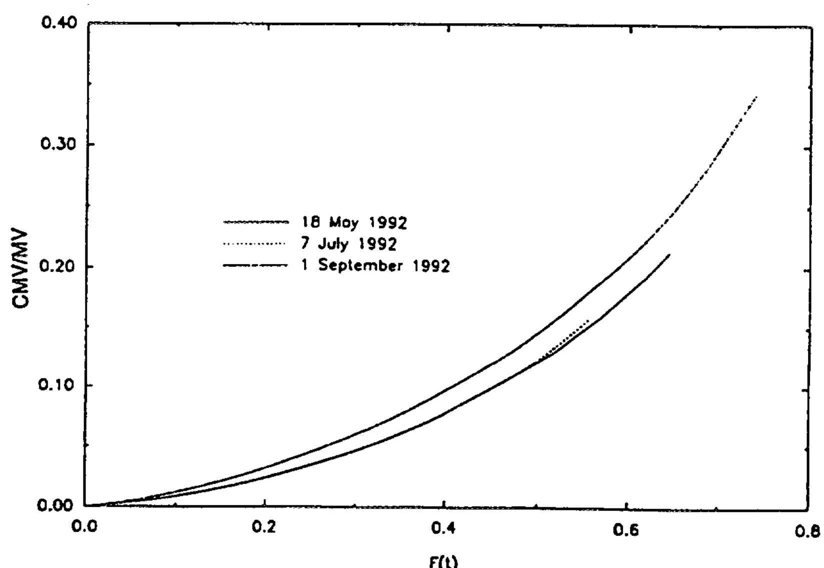


Figure 3 - Comparison of F(t) and χ(t) for the LTFT tracer tests at Fenton Hill.

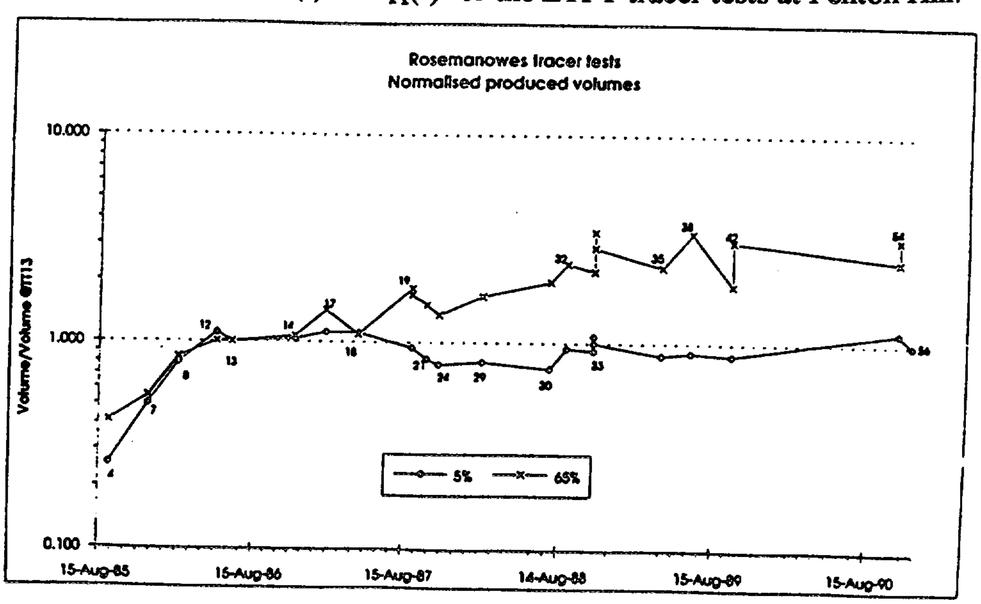


Figure 4 - Rosemanowes: normalised produced volumes of fluid at different percentiles of tracer recovered (TT04 to TT56).

Annex

Definition of some functions

$f(t).dt$ = probability that a particle of the produced fluid picked at random has a residence time between t and $t+dt$; alternatively it represents the fraction of the (steady state) flow rate with a residence time between t and $t+dt$.

$\chi(t).dt$ = probability that a particle picked at random inside the system will have a residence time between t and $t+dt$; alternatively it is the fraction of the volume of particles inside the system that will have a residence time between t and $t+dt$.

The relation between $f(t)$ and $\chi(t)$ is:

$$\left(\chi(t).dt\right)=\left(\frac{t}{\bar{t}}\right)\times\left(f(t).dt\right)$$

i.e. $\chi(t).dt$ can be understood as a fraction of volume, as $f(t).dt$ is easier to picture as a fraction of flow rate.

$\bar{t}$ represents the mean residence time and it is calculated as:

$$\bar{t}=\int_0^\infty t.f(t).dt=\frac{\bar{V}}{Q}$$

where:

$\bar{V}$ is the volume of the system open to fluid flow (L^3);

Q is the (steady state) flow rate ($L^3.T^{-1}$).

The cumulative functions of $f(t)$ and $\chi(t)$ are:

i) The external residence time distribution function:

$$F(t)=\int_0^t f(t').dt'$$

where t' is a dummy variable (T).

This function results directly from a positive step tracer test.

ii) The internal residence time distribution function:

$$\mathrm{X}(t)=\int_0^t \chi(t').dt'$$

A graph of $F(t)$ versus $X(t)$ provides a picture of the fraction of the volume of the system swept by a given fraction of flow rate.

Reference:

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An Analysis of the Growth of HDR Reservoirs during Circulation using Tracer Data and Numerical Modelling of Thermo-Elastic Effects

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It has been generally assumed that the thermal performance of HDR reservoirs will deteriorate with time. The argument is that the short residence time flow paths, or short circuits, cool fastest and, as a result of thermal contraction of the rock mass, their aperture increase more than the long residence time flow paths. This leads to an increase in flow in short residence time flow paths resulting in thermal drawdown occurring more rapidly. In other words HDR reservoirs should get worse with time not better!

However the analyses of tracer data from reservoirs that have exhibited thermal drawdown during long term circulation seem to contradict this view indicating that it is the longer residence time flow paths that take more flow as the reservoirs cools. The median volume at the Rosemanowes reservoir grew from 500 m^3 to 2500 m^3 between 1985 to 1988 (Figure 1) and the mean volume of the Fenton Hill reservoir increased 23% in two months in 1992 (in May it was 2246 m^3 and in July was 2766 m^3, table below).

Table - Evolution of some parameters
Rosemanowes

	October 1985	June 1986	November 1988
Breakthrough volume (m^3)	58	107	48
Median volume (m^3)	469	1147	2420
Mean volume (m^3)	719	1406	2891

Fenton Hill

	May 1992	July 1992	September 1992
Breakthrough volume (m^3)	79	110	96
Median volume (m^3)	1200	1615	1240
Mean volume (m^3)	2246	2766	2044

In order to reconcile the above contradictions long term circulation modelling was carried out with a 2D computer code HOTGRID from the FRIP family of codes, that couples mechanical, hydraulic and thermal behaviour for fluid flow in fractured rock mass. A number of different cases were run. Figure 2 shows the results of a model run for an HDR system comprising a circulation between an injection and production well 120m apart in an anisotropic stress field similar to Rosemanowes at 2,2 km depth.

In this case the thermal breakthrough was rapid with the production temperature falling from 100 °C to 85 °C in 6 months (with a behaviour similar to that attributed to the short circuit path of Rosemanowes). The volume open to fluid flow increased throughout the circulation with the major increase in aperture occurring in flow paths parallel to the direct connection but in parallel paths further from the wells.

The results of all tests of the numerical modelling showed that thermo-elastic effects did invariably increase the volume of the reservoir open to fluid flow. However depending on the local conditions this might either lead to the opening of the shorter residence time flow paths causing an increase tendency for short-circuiting or lead to the opposite effect and cause the opening of new and hotter flow paths. In both situations however the thermo-elastic effects only accounted for less than 5% of the increase in the volume open to fluid flow during steady state circulation of up to 10 years. The parameters that seem to most affect the results are: (i) the stress field, (ii) the number and distance between wells, and (iii) the imposed flow conditions.

In conclusion:
i) Since the median volume at Rosemanowes increased 500% from 500 m^3 to 2500 m^3 over a three year period, it therefore seems unlikely that thermo-elastic effects can explain the large increase in the volume open to fluid flow during the circulation of the Rosemanowes reservoir (or the Fenton Hill reservoir);
ii) All the numerical runs showed an increase in the volume of the simulated reservoirs. However all the variations in volume were less than 10% in ten years due to heat extraction alone. The paths that vary the most are not necessarily the most direct connections.

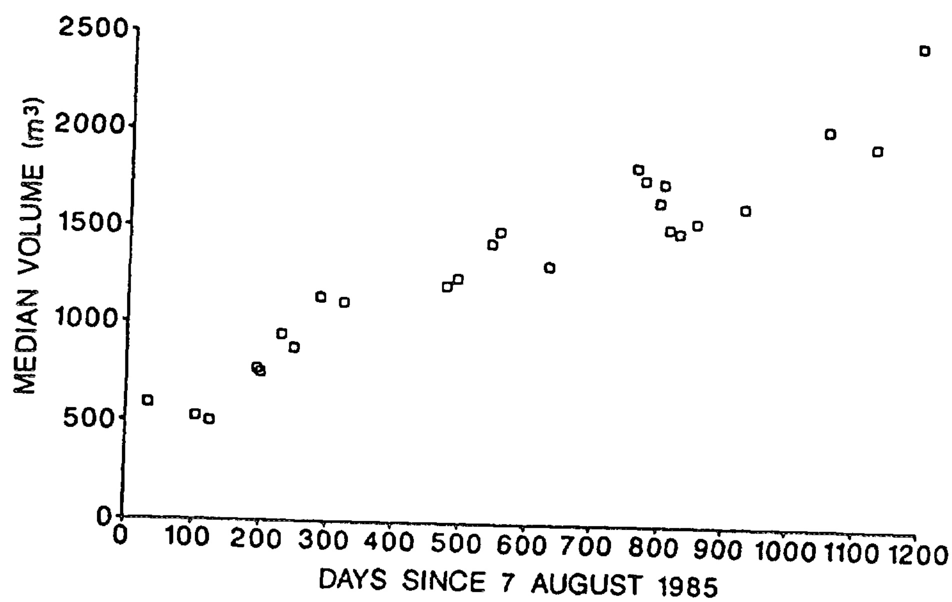

Figure 1 Median Volume of the RH12/RH15 Rosemanowes system during circulation.

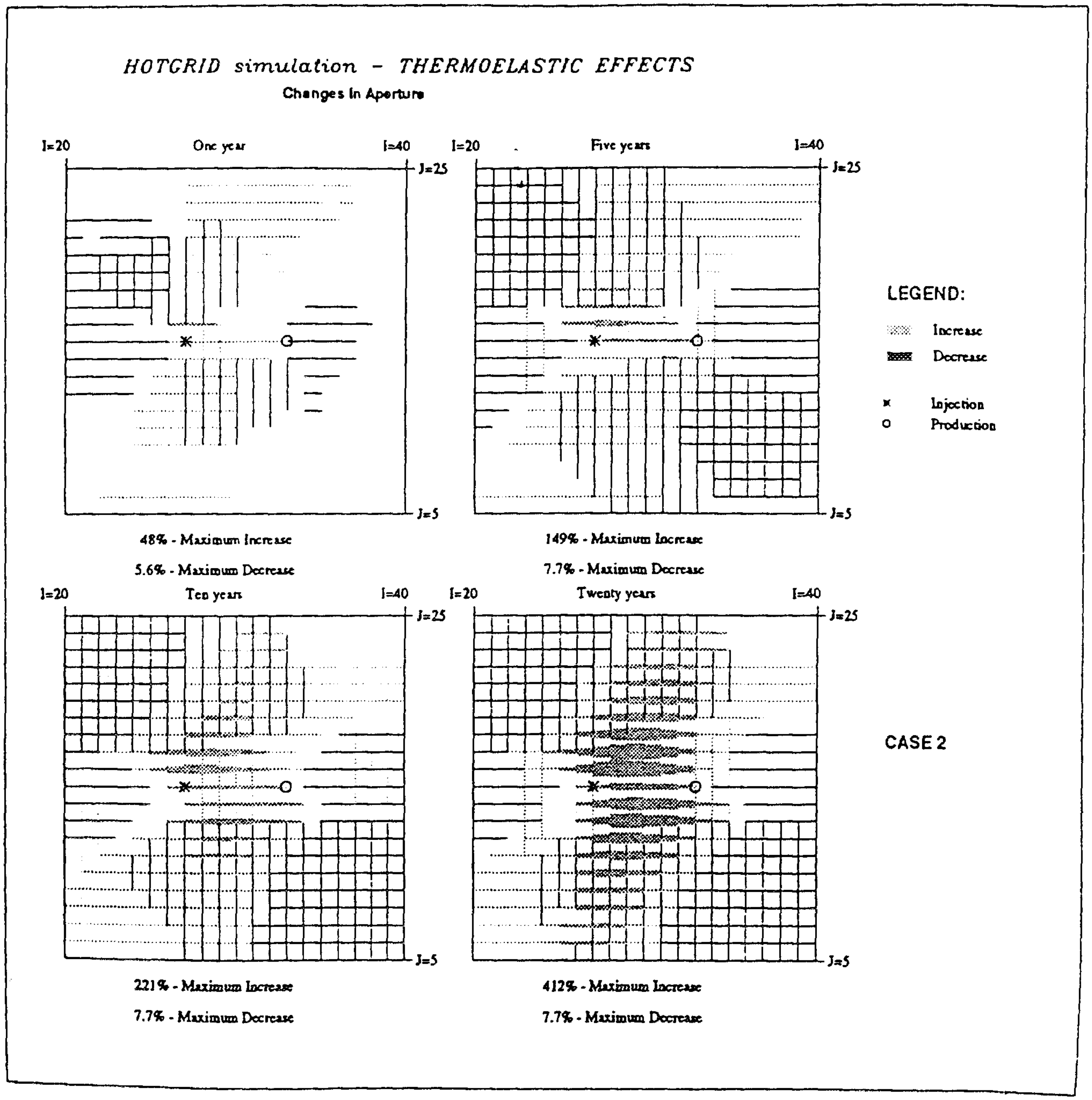

Figure 2 Thermally induced fracture aperture changes due to circulation.

A CROSSHOLE SEISMIC SURVEY OF THE INFLATED HDR RESERVOIR IN FJÄLLBACKA, SWEDEN

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A research project, co-financed by the CEC (Thermie) and the Swedish National Board for Industrial and Technical Development (NUTEK) was completed in Fjällbacka during 1995. Two crosshole seismic surveys were carried out over the well-characterised HDR reservoir connecting two boreholes at 450 m depth. The overall aim of the project was to demonstrate the viability of a borehole seismic reflection / transmission tomography technique for the imaging of fluid bearing fracture zones. By conducting the same survey at ambient downhole pressure and at an elevated pressure, the experiment was also aimed at investigating the effects of pressurisation.

The fractured reservoir connects the two 500 m deep boreholes over a horizontal distance of 100 m. Information on the characteristics of the reservoir has been obtained from analysis of induced microseismicity and from evaluations of various hydraulic tests. However, insufficient knowledge of the interwell region has limited the possibilities to produce a total image of the flowing zones connecting the boreholes.

The surveys were carried out using a sparker seismic source deployed in Fjb3, which dips at about 80° to the horizontal, and a string of four hydrophones deployed in Fjb1, which is near vertical. The survey depth range was between 400 m and 480 m beneath ground level. During the pressurised survey, inflatable packers were used to isolate the test sections of the boreholes below 350 m depth. The packed-off region was pressurised by pumping water into the tubing of Fjb3, the source well, whilst Fjb1 remained shut in. The pressurised seismic survey was carried out at a pressure of 3.2-3.4 MPa above hydrostatic, which was considered sufficient to open up the fracture system.

Data processing involved tomographic imaging, wavefield processing and wavefield migration imaging. From difference images, formed by subtracting the pre and post pressurisation tomograms and wavefield images, fracture zones opened by the pressurisation could be identified (see figures 1 and 2).

We were able to correlate most of the imaged structures with known fractures and lithology contrasts. By integrating seismic data with borehole and hydraulic data a much greater understanding of the distribution and significance of open fractures within the reservoir could be obtained. The extent of fracture opening due to the reservoir inflation was illustrated in the wavefield from the pressurised test as strong events produced by increases in reflectivity. In particular, the interpretation of the crosshole data suggested that there are comparatively few fractures linking the main flowing zone in the injection well to the more spatially extensive flowing zones in the recovery well. This interpretation is consistent with the results of earlier flow tests which found a high hydraulic impedance between the wells.

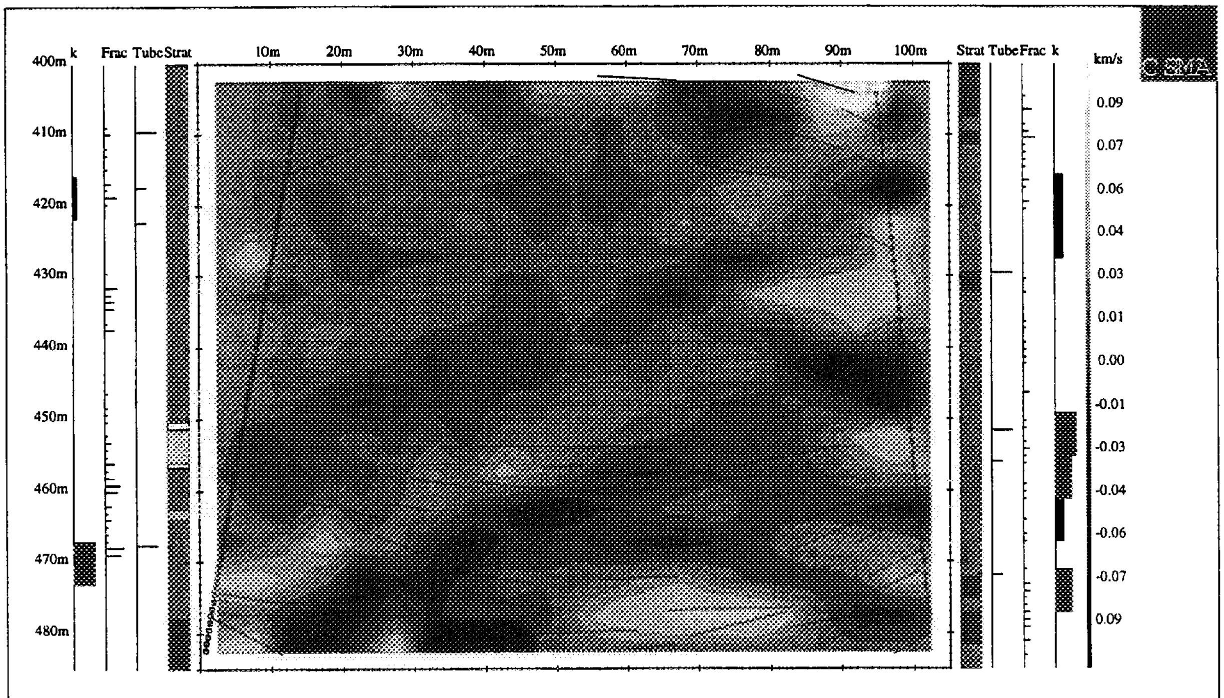

FIGURE 1 DIFFERENCE VELOCITY IMAGE WITH INTERPRETED REFLECTORS SUPERIMPOSED

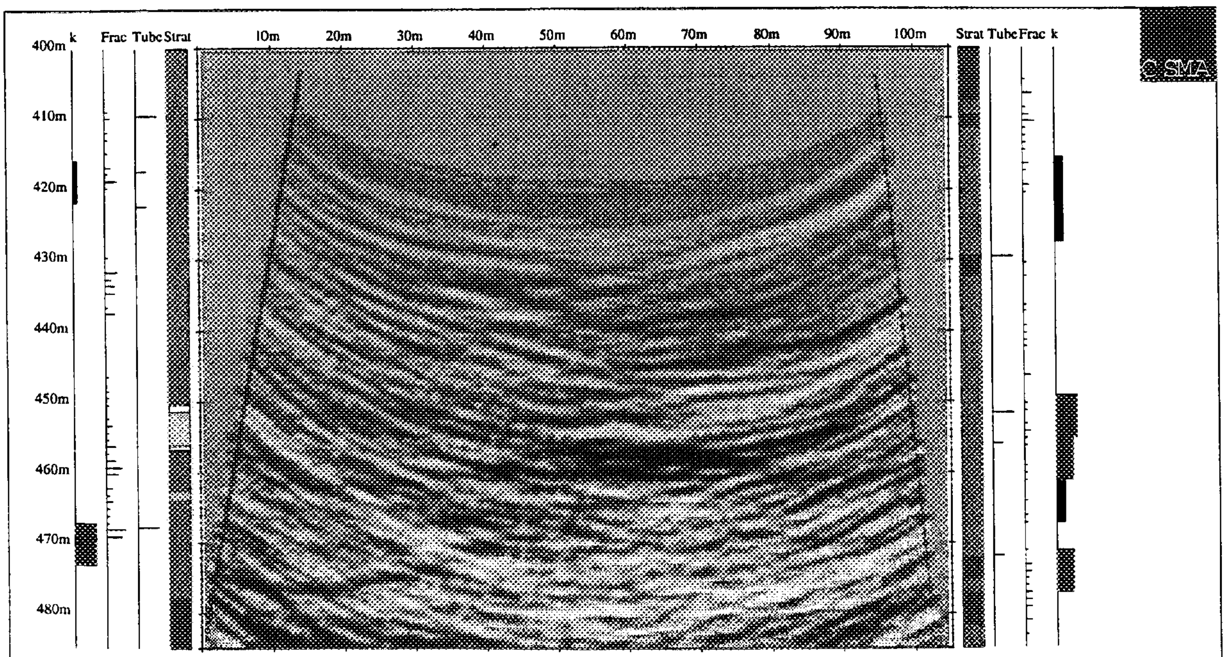

FIGURE 2 DIFFERENCE WAVEFIELD LOOKING DOWN = PRESSURISED - UNPRESSURISED WAVEFIELDS. GLOBAL SCALING. POSITIVE VALUES ARE WHITE.

Fracture Monitoring by AE and Electrical Prospectings

by

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Abstract: An advanced geophysical technique for reservoir monitoring has been carried out by the joint use of Acoustic Emission (AE) Survey, Charged Potential (CP) and Spontaneous Potential (SP) methods since HDR project has started at Ogachi area in 1989. The present charged potential method utilizes a steel casing pipe itself as a current electrode similar to the mise-a-la-masse method utilizing a buried point source in the target. These seismic and electrical methods had been applied to monitor fluid-flow behaviors during massive hydraulic fracturing operations for creating fractures and water circulation tests through two fractures from a injection to a production boreholes. Acoustic emission events, charged potentials (mV/A) and spontaneous potentials (mV) were continuously measured as a function of time at multiple stations surrounding operating boreholes by the automatic recording system controlled by a personal computer. Fluid flow behaviors in the subsurface could be visualized as a function of time by AE hypocenter distribution and computer animations of time-sliced contour maps of residual potentials from SP data and relative changes of apparent resistivity distributions caused by dynamic reservoir simulations.

INTRODUCTION

Various geophysical exploration techniques have been applied to the problem of detecting fractures and fluid flows in the subsurface. The most used geophysical methods are seismic and electrical resistivity methods. At the Ogachi HDR site, acoustic emission events were monitored by three-components geophones at 8 stations in depths of 30 to 50 m. Signals detected by these geophones were band-pass filtered between 10 Hz and 1 kHz and digitized by 2 kHz sampling interval. Charged potential method as shown in Figure 1 has been mostly used for detecting an anomalous body such as geothermal fractures in Japan.

Fluid-flow behavior can be continuously measured with a personal computer and observed electric potentials (mV/A) converted to apparent resistivity data and self potentials (mV) are automatically processed by a personal computer according to the flowchart as shown in Figure 2.

3D Numerical Modeling

Charged potential data using a line source electrode are interpreted by numerical scheme for an arbitrary three-dimensional model in a half space. Using the computer program (VEP3D), a series of apparent resistivity responses have been computed for various models with an arbitrary length of casing pipe and position of a current electrode in the subsurface. Self Potential anomalies due to streaming potential effects have been simulated by the crosscoupled equations for fluid flow and electric current.

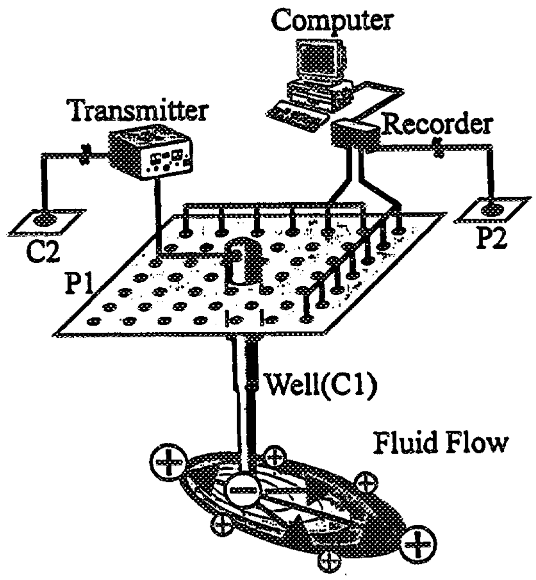

Figure 1. Electrode Configuration.

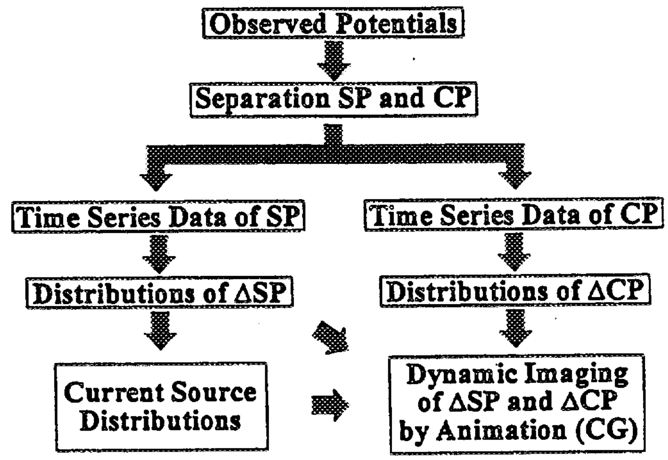

Figure 2. Data Processings.

OGACHI HDR SITE

AE, CP and SP measurements were conducted during hydraulic fracturing experiments in 1,000 m deep fracturing well (injection) and production well into two-stage fractures as a function of time in pre-tertiary granitic formations. Fluid-flow fronts were monitored by AE hypocenter distribution and the location of SP anomalies with a function of time.

The injected water distribution during fracturing operations could be evaluated by AE hypocenter distribution and apparent resistivity anomalies.

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International: SEG, EAEG, IEEE.

Area of Professional Interest and Other Information: Automatic data processing of geophysical data.

THE APPLICATION OF GEOSTATISTICAL TECHNIQUES TO THE ANALYSIS OF MICROSEISMIC CLOUDS

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Microseismic mapping provides the primary geometrical information about HDR reservoirs. The production and interpretation of reliable microseismic locations are of central importance in the evaluation of HDR reservoirs, particularly for issues such as well placement. The objective evaluation of a seismic cloud is not a simple problem, the data set may be very large and is multi-dimensional. The semivariogram, a technique developed in the field of geostatistics, can be usefully applied in the evaluation of seismic clouds.

The semivariogram is a graphical device for modelling spatial continuity. If we define z(x) as the value of some variable at a site x and z(x+h) and the value of the same variable at some distance h from x, then the semivariogram is defined as

$$\gamma(h) \quad = \quad \Sigma[(z(x) - z(x+h))^2]/2n$$

where there are n pairs of points. In practice, for irregular data the semivariogram is calculated for distance intervals via a binning process, the values within each bin being averaged. A major assumption in the calculation is that of stationarity, that is that the value of the variable does not have a trend right across the area of interest.

In the analysis of seismic clouds we may regard the value of a channel residual as the quantity of interest and its spatial position to be that of the hypocentre. The semivariogram can be used to investigate the structure of the spatial dependence of channel residuals, which ideally should be random.

Semivariograms are typically fitted to models of varying degrees of complexity but a few general features are typically present, as shown in Figure (1). Figure (1a) shows a semivariogram resulting from a random process. Figure (1b) shows a more typical results where γ increases with distance until it reaches a constant level, or sill. Figure (1c) shows a continuously increasing γ, in this case the assumption of stationarity is violated, the variable changes value right across the area of interest, this trend is known as drift.

Figure (2) shows two examples of semivariograms for p-timing data from a single sensor (4616) for the 1995 stimulation of GPK2 at the Soultz-sous-Foret site in France. The heavy lines shows the actual semivariogram obtained from the data after joint hypocentre location. The presence of a sill which is less than 25% greater than the nugget suggests that the channel residuals are almost randomly distributed. This is interpreted as indicating that the isotropic velocity model used for the granite is appropriate.

The lighter line on Figure (2) is the result of imposing a depth dependent channel residual, which mimics the effect of an inappropriate velocity field. This results in a semivariogram showing drift.

In conclusion I suggest that the semivariogram is a simple practical tool for investigating in a quantitative way, the structure and reliability of microseismic clouds.

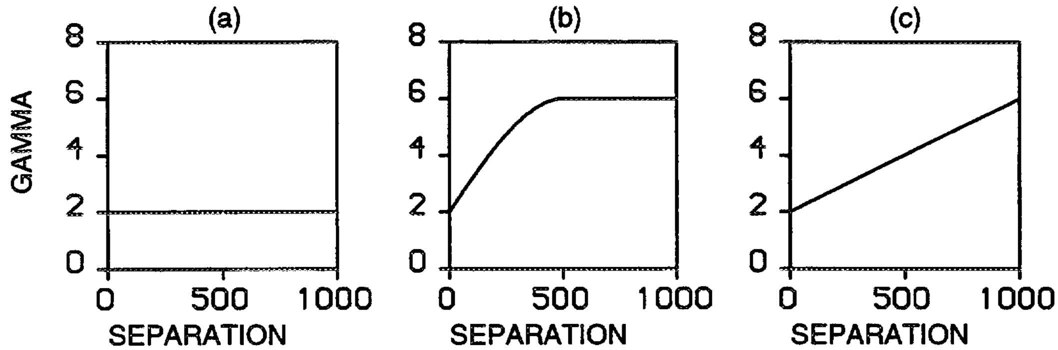

FIGURE 1 Semivariograms
(a) pure nugget effect of value 2
(b) nugget of 2 with a sill of 6 and a range of 500
(c) nugget of 2 and a constant gradient, termed drift

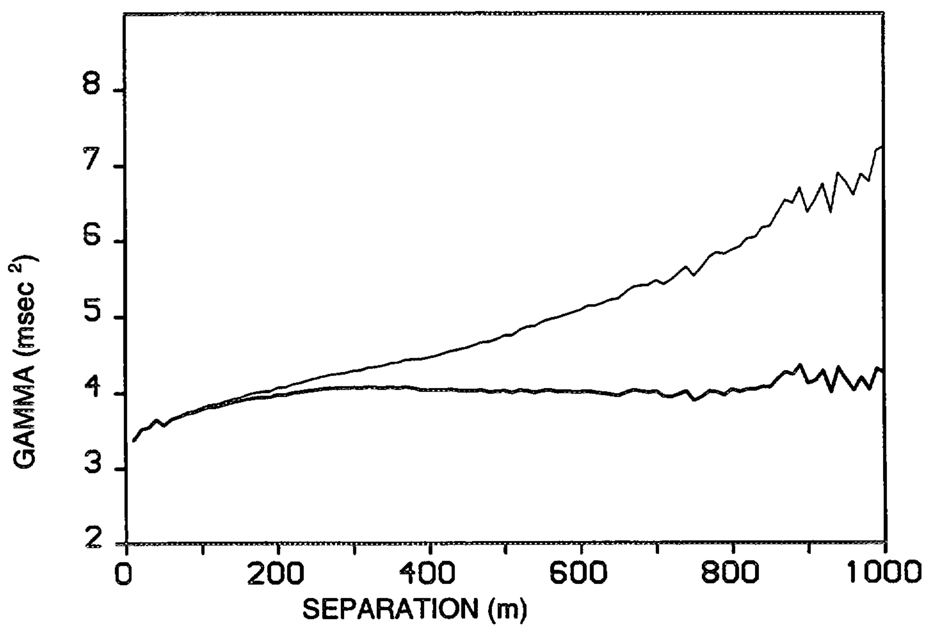

FIGURE 2 Semivariogram for Soultz 95 JHD locations (thick line) and with a systematic depth dependent residual of 1 msec/kilometre superimposed on the actual data (thin line)

Transition of Fundamental Nature of a Reservoir System Consisting of Multiple Cracks Due to Hydraulic Stimulation with Application to a Model Field

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It is well known that artificial geothermal reservoirs created by hydraulic fracturing, consist of multiple reservoir cracks along planes of weakness. However, neither the growth process nor the transition of the fundamental nature of such reservoir systems have been clarified yet. In the present paper, we present a simple model . The basic ideas of the model are as follows. The reservoir consists of penny shaped cracks developed along planes of weakness. The stress intensity factor on the periphery of each crack is equal to the fracture toughness of the plane of weakness. The fluid flow in the cracks is turbulent and is described by the following equation as a first order approximation:

$$\frac{dp}{dr} = -\frac{\lambda}{8w^3} 2\rho q^2 \tag{1}$$

Here, w is the aperture of the crack, p is the pressure of the fluid, r is the radial distance from the center of the crack measured along the crack, ρ is the fluid density, q is the volumetric flow rate in the crack per unit length along the cirumferential direction. The coefficient λ is given by

$$\lambda = 0.5 / \left(\log \frac{k / D_h}{1.24}\right)^2 \tag{2}$$

where k is the roughness of the crack surface and D_h is the hydraulic diameter of the flow path along the crack. According to the model, the growth of the crack is primarily divided into two cases depending on the injection flow rate and the fracture toughness of the plane of weakness. When the flow rate is low and the fracture toughness is large, the pressure at the crack mouth decreases with crack growth. On the contrary to this, when the flow rate is large as usually used in stimulation of geothermal wells and the toughness along the plane of weakness is small, the pressure at the crack mouth increases with crack growth. These two cases are summarized in Figure 1. The bottom line in Figure 1 is the example of the case controlled by the fracture toughness and the upper three lines are the examples of the case controlled by the flow resistance. Finally, we applied the model to the Unomori field to study the morphology of the reservoir in the field. In the Unomori field, the stress field, wellbore logging data obtained by BHTV and FMI, spinner logging data are available. By using these basic data, we examined the variation of the reservoir system with respect to the injection flow rate. Results are summarized in Figure 2, where the short lines are the cracks activated by the fluid injection at the flow rate shown in the bottom of the each figure. The inclination of each short line shows the dip of each crack observed by BHTV and FMI logging. It is seen that the morphology changes at about 200-250m³/h . When the flow rate is lower, the reservoir consists of cracks which are almost vertical, but it consists of both of the vertical cracks and the oblique cracks when the flow rate is larger. This accords well with the results estimated by using AE observed during the hydraulic stimulation.

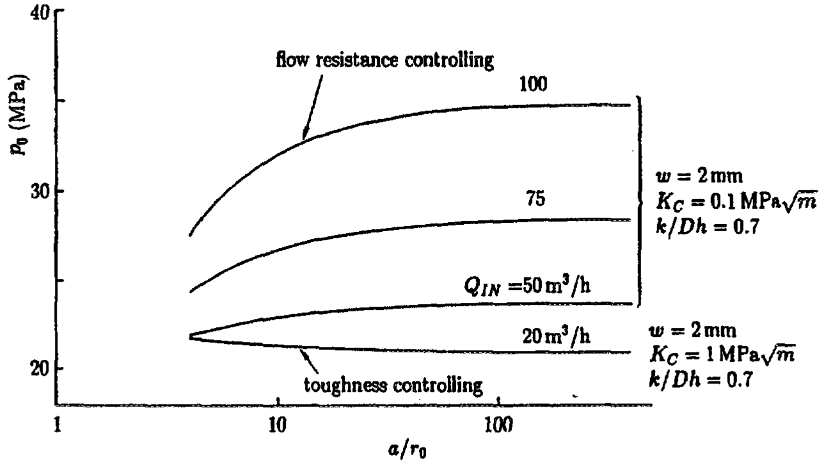

Figure 1. Variation of wellbore pressure p_0 at the crack mouth with crack radius a (S= 20MPa), r_0 : wellbore radius, S : stress acting normally to the crack.

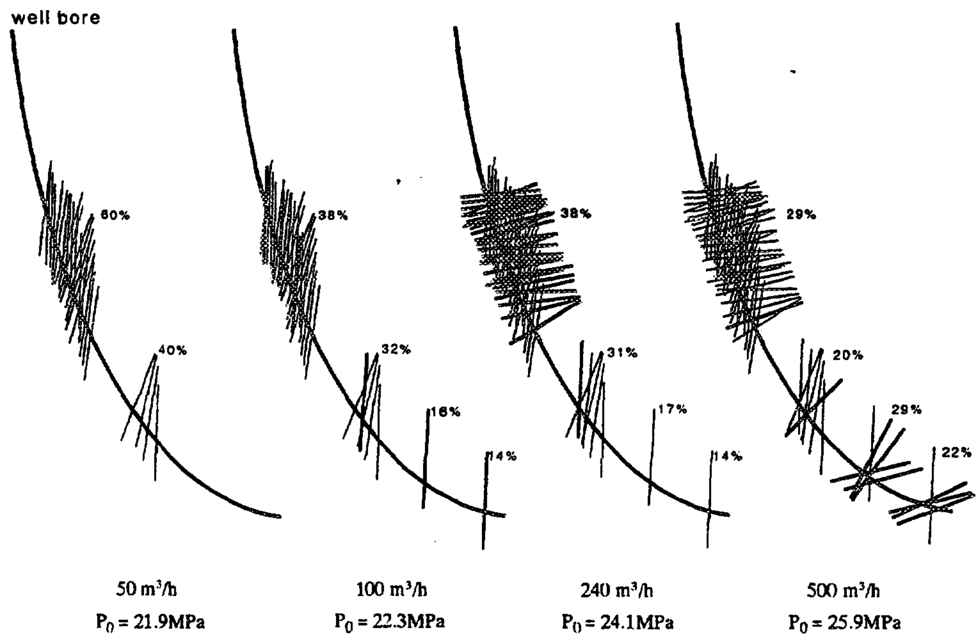

Figure 2. Transaition of morphology of the reservoir system. The numbers in the figure show the ratio of the flow rate flowing into each depth to total flow rate injected.

Modeling Fluid Circulation and Heat Exchange at HDR Test-Sites by Discrete Fracture Network Models

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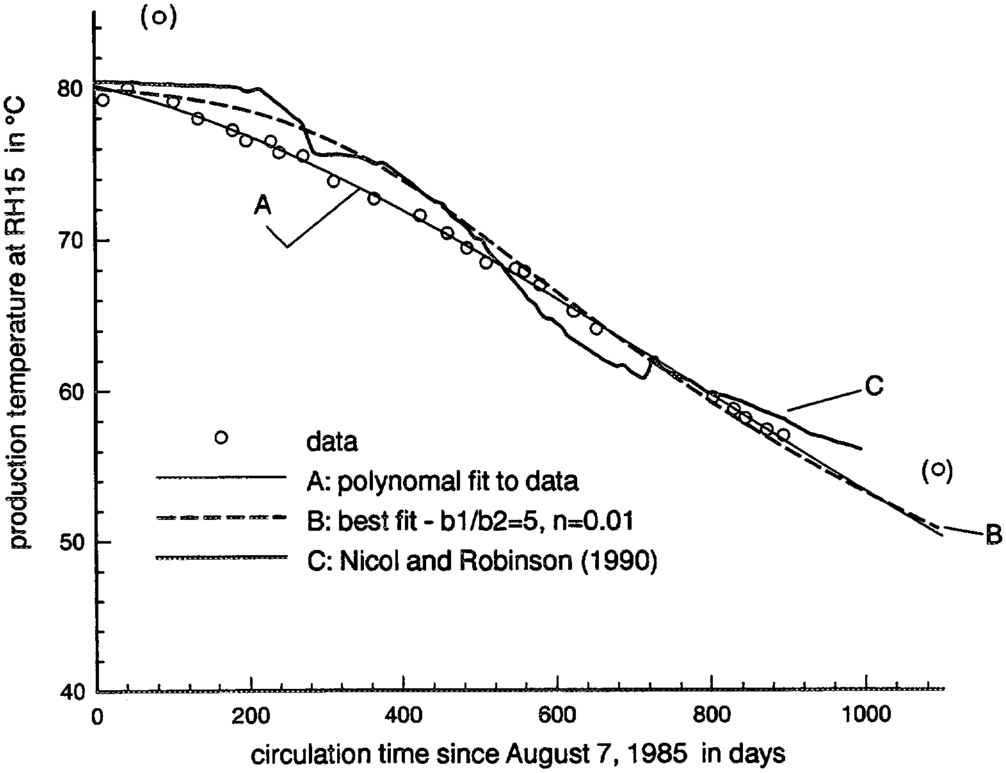
Records of pressure and temperature drawdown during long-term circulation tests at the European HDR sites Rosemanowes (UK) and Soultz-sous-Forêts (France) provide constraints for numerical simulations of fluid and heat flow in a fractured HDR reservoir. Our modeling strategy aims for a balance between the complexity of the simulated fracture network and the number and quality of the available data. A simplified deterministic fracture network, based on the mapped fracture inventory and the prevailing stress field, is imbedded in a porous matrix. Hydraulic impedance is used as a lumped parameter to describe the hydraulic response of the tested reservoir. Results of 3D-simulations of fluid circulation and heat exchange in the reservoirs are compared with experimental data.

A long-term circulation experiment in two wells of the Rosemanowes HDR site extended over a period of about three years. The size and the shape of the accessible reservoir was estimated from the micro-seismicity recorded during the stimulation of the wells. From a statistical analysis of the data two subvertical sets of fractures were identified, which scatter around the two major strike directions of 165° N and 250° N. Therefore, a deterministic fracture network was set up according to these average orientations. Further, the number of fractures is restricted to those, which actually absorb water as detected by the well logs. The observed anisotropy in the tectonic stress field implies anisotropy also in the hydraulic behavior of the fracture system. Aperture widths were fitted for different anisotropy factors according to the measured hydraulic reservoir impedance of 0.6 MPa l s^{-1}.

The thermal model was calibrated to the production (bottom-hole) temperatures. The influence of several factors on the simulation results were studied in particular, such as the initial temperature distribution, hydraulic anisotropy (expressed as aperture ratio b1/b2 of two sets of quasi orthogonal fractures), and matrix porosity n (Kolditz et al. 1995). The hydraulic characteristics of the fracture network are strongly affected by the in situ tectonic stress field, which causes anisotropy also in the hydraulic behavior of the fracture system. A model with an anisotropy factor of five and with a matrix porosity of about 1 % provides the best fit to the data (see Figure below). Such values of hydraulic anisotropy are confirmed by previous studies of Hodgkinson (1984) and Jung (1991). These results are compared with earlier findings of Nicol & Robinson (1990). The figure illustrates the improvement in respect to an interpretation of the experimental field data which can be obtained by the hybrid modeling approach.



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Assessment of Heat Mining from Hot Dry Rock Based on Fractal Fracture Network Model

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A three-dimensional subsurface fracture network model is proposed on the basis of "fractal geometry". The network is generated by distributing a fractal size distribution of penny-shaped fractures with random orientations to random positions in the cube. Using this fracture network model, a parameter study of the performance of Hot Dry Rock geothermal energy extraction systems is performed. Geothermal energy extraction performances from the single fracture and permeable zone models are also estimated, since these will provide, respectively, the lower and upper bounds of the reservoir performance. Fig. 1 illustrates the three-dimensional single fracture, fracture network and permeable zone models used in this study.

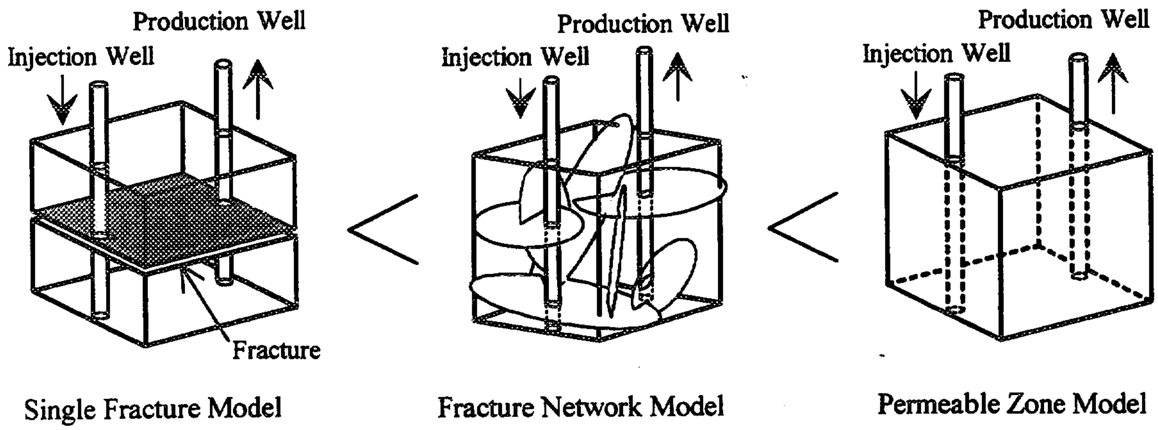


Fig. 1 Estimation of energy extraction from Hot Dry Rock based on the single fracture, fracture network and permeable zone models.

In the numerical calculation, parameters are normalized. Fig. 2 shows the changes in normalized thermal energy output, E^* with normalized time, t^* for above models. The normalized quantity of circulation water, Q^* is fixed to be 100, and the fracture density of the fracture network model, C is changed to be 2, 4 and 6. The quantitative values in table 1 are the transformations of above normalized values as functions of the distance between two wells, L. Although the normalized quantity of circulating water is fixed in above analysis, it is also important to estimate optimum quantity of circulating water, Q^* for effective heat mining from HDR. The normalized reservoir lifetime, t_{life}^* is defined as the point where the normalized temperature of production water reaches the normalized lowest temperature, T_{th}^* at which economical energy production is possible as shown in Fig. 3. Once T_{th}^* is fixed, and the fracture density is obtained, t_{life}^* can be predicted as a function of Q^*. In this study, the values of Q^* which give the same value of t_{life}^* as the design lifetime are estimated, and this value of Q^* for each system is defined as the normalized optimum quantity of circulating water. Fig. 4 shows the relationship between reservoir size L (m) and maximum energy output, E_{max} (MW) with optimum quantity of circulating water. It can be predicted that a 2 km x 2 km x 2 km HDR reservoir which has a relatively high fracture density ($C > 4.0$) can produce more than 300 MW under optimized operational conditions.

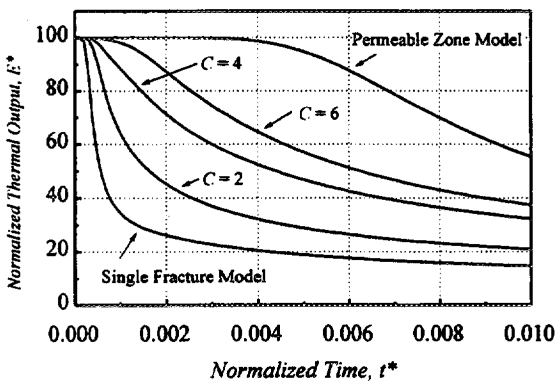


Fig. 2 Change in thermal energy output, E^* with time, t^*.

	L=200m	L=600m	L=1000m
$Q^* = 100$	44 m^3/h	133 m^3/h	222 m^3/h
$t^* = 0.01$	17 years	151 years	420 years
$E^* = 100$	4,799kW	14,396kW	23,992kW

Table 1 Series of transformations from normalized values to quantitative values.

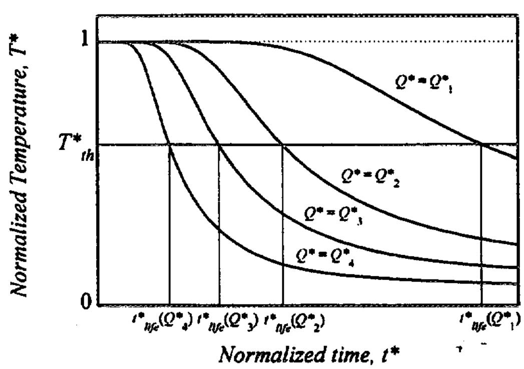


Fig. 3 Definition of the system lifetime and the influence of the quantity of circulating water.

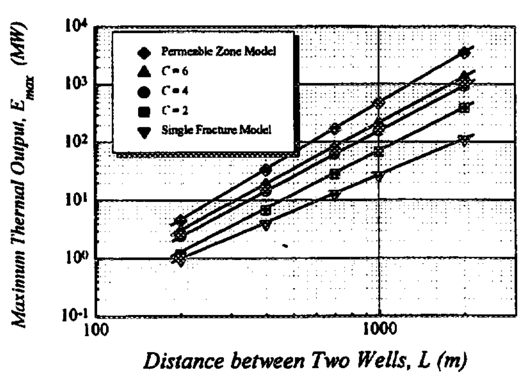
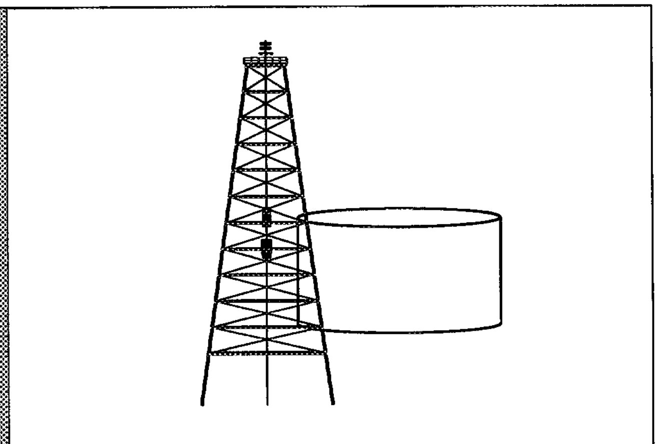


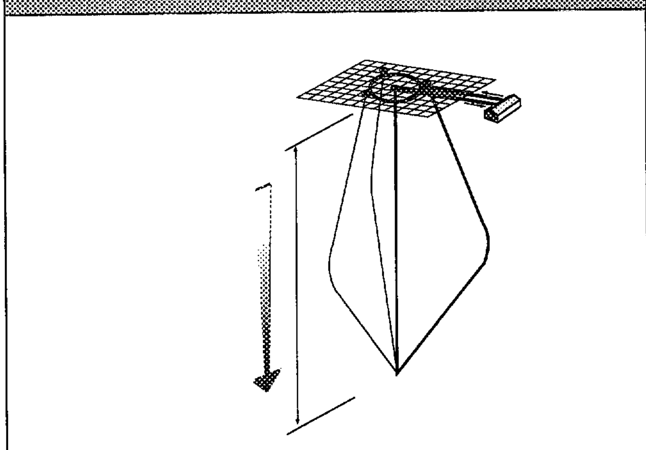
Fig. 4 The maximum thermal energy output from optimized HDR systems.

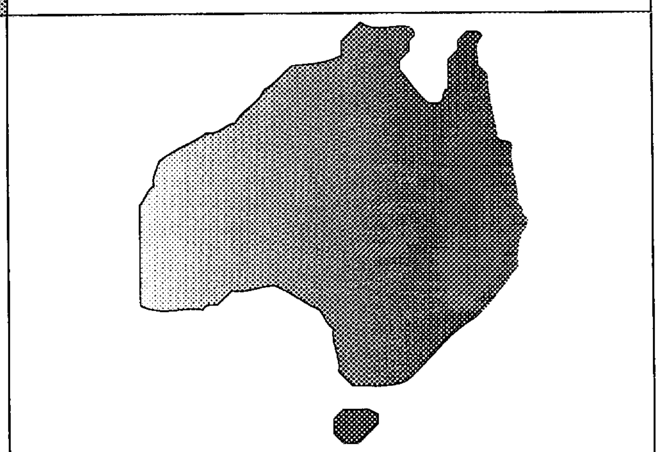
The fractal fracture network model can be used for the estimation of the performance of geothermal reservoirs in fractured rock, and bridges the gap between the single fracture and permeable zone models. By using the fractal model, it is possible to predict the long-term heat energy output of a geothermal reservoir as a function of fracture density. The analysis of energy extraction from optimized HDR systems indicates that energy extraction from geothermal reservoirs with multiple flow paths, that is, high fracture density in the rock mass, can be considered as having a high potential as a new energy extraction technique.

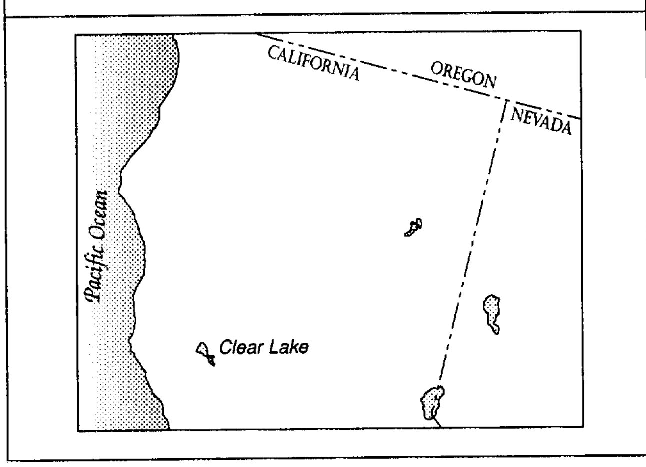
Session 9:
Reservoir Assessment and New Technology

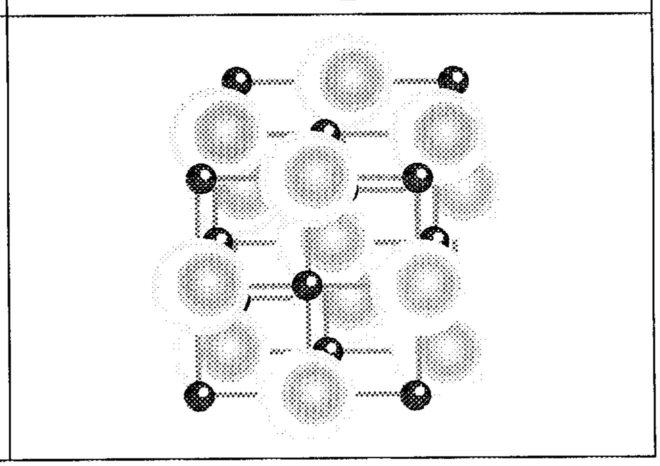
Session Chair: Gladys Hooper











TOWARDS HOT DRY ROCK DEVELOPMENT IN AUSTRALIA

Doone Wyborn, Principal Research Scientist
Australian Geological Survey Organisation (AGSO)

Hot dry rock geothermal energy potential in Australia was first brought to public attention in 1985 by Bob Koch, a BP petroleum development manager, when he stated in a South Australian Chamber of Mine publication that "the Cooper Basin must be one of the most significant geothermal areas in the world". Koch had experienced oil exploration all over the world, and did not know of another basin region with such high geothermal gradients. Discussions with CSMA and LANL followed, but the proposal for experimental development did not go ahead as enthusiasm was lost when Koch became ill.

In October 1993, Koch's vision was rekindled when a HDR conference, with guest speakers from CSMA and LANL, was held in Canberra sponsored by AGSO and the Australian governments Energy Research & Development Corporation (ERDC). As a result of that conference an Australian HDR study was commissioned, and a working party was set up of interested government and industry partners. The objectives of the study were fourfold: to provide analyses of Australia's HDR resources, the technologies required by HDR, the economics of HDR in an Australian setting, and to scope and cost future phased HDR research work in Australia.

The study was published in December 1994 by ERDC, and showed that prospects for HDR development in Australia are favourable in terms of the scale of the resource, the efficiency with which the resource could be exploited, and the cost of developing the resource. Four factors responsible for these conditions are independent of one another, and can be summarised as follows: (1) the large scale of the resource stems from the thermal blanketing effect of sedimentary basins which cover nearly half of Australia's land surface. (2) the abundance, particularly in central Australia, of high-heat-production basement rocks, particularly granites, which make Australia unique. (3) the anticipated efficiency of resource exploitation derives from the crustal-shortening stress regime of most of the crust in Australia. This should result in favourable reservoir orientations (horizontal or sub-horizontal) and minimise leakage of water from reservoirs.
(4) a relatively low cost of resource development is anticipated because of the ease of drilling through sedimentary basins to basement, and the absence of a need for inclined drilling in basement if, as expected, the reservoir orientation is horizontal or sub-horizontal.

These factors place Australia in a particularly good position to play a leading role in the future global development of HDR energy. In addition to technical factors, there is an economic factor, the demand for small-scale remote power generation, adding to the prospects for early HDR development in Australia. The resource assessment component of the study was based on the compilation of a database of nearly four thousand borehole temperatures. An important result is a significant spatial correlation between high geothermal gradients and low gravity zones within the basins, resulting from the presence of low-density high-heat-production granites below the basins.

Potential energy reserves for electric power generation ranging from thousands to millions of petajoules are accessible below Australian sedimentary basins. The basins below which significant HDR resources were identified are in order of resource size, the Eromanga, McArthur, Otway, Carnarvon, Murray, Perth, Canning, East Queensland and Sydney Basins. The Eromanga Basin has by far the largest potential of these basins (83%), conservatively estimated at 19 million petajoules to a depth of 5 km.

The calculated HDR resources in favoured granite bodies beneath the Eromanga Basin amount to 2.5 million petajoules, 830 times Australia's current energy consumption. Two regions of granite have outstanding potential, the Innamincka gravity low in NE South Australia and the Betoota gravity low in SW Queensland, where each gravity low is considered to represent a granite body with a temperature of 300xC at 5km. The resource is contained in over 1000 cubic kilometres of granite in each of these two regions, either of which could supply the energy equivalent of 90 times Australia's annual consumption. At a less remote site, beneath the Sydney Basin south of Muswellbrook, an area of high geothermal gradient corresponds to a gravity low thought to be a buried granite body with an estimated 75 cubic kilometres of HDR resource at an average temperature of 250xC.

In crustal-shortening stress regimes, which are prevalent in Australia, reservoir growth is expected to require fluid pressures matching or exceeding the overburden stress, and the reservoir is expected to be horizontally elongated. By contrast, all of the major HDR reservoir experiments to date have been carried out in extensional or wrench stress regimes, generating vertically-elongated reservoirs at fluid pressures less than the overburden. Horizontal reservoir orientation and vertical injection and production wells represent the optimum geometrical configuration for reservoir engineering.

In the Australian environment a cost price of below A$100/MWh was calculated for the operation of a 20MWe output HDR power plant with a minimum life of 30 years. A 20MWe plant designed around a reservoir of 1 cubic kilometre at 250xC was costed at A$60.4 million. A larger development of 100MWe utilising the anticipated horizontal reservoir orientation, and requiring nine wells gives an estimated cost of A$50/MWh.

In March 1995, Hot Rock Energy Pty Ltd, was set up with 15 partners. The company will apply to the Australian Government for 150% tax concessions for investors who support a two-well circulation experiment at the Sydney Basin site. It is anticipated that this project will be seeking investment in late 1996.

Another, less ambitious project is expected to commence at about the same time in the Cooper Basin in South Australia. This project will investigate the fracture potential of the deep tight gas resources of the basin, and of the immediately underlying granite. It will thus provide potential information towards development of both gas and HDR resources, and will be the first study in Australia to measure acoustic emissions during fracturing.

DOWNWARD-CONTINUATION OF HEAT FLOW FOR HOT DRY ROCK SITE SELECTION IN ROCKS OF THE THE PACIFIC RIM

K.L. Burns and M.J. Burns

HOT DRY ROCK (HDR) RESOURCES

Hot Dry Rock (HDR) resources in continental regions have been envisaged as essentially layered and homogeneous for the purpose of resource assessment. However this concept is inapplicable in Pacific Rim terrains, where the geothermal resource is a heterogeneous assemblage of conductive and hydrothermal regimes.

In The Geysers-Clear Lake area, three geothermal regimes co-exist: vapor-, conduction-, and liquid-dominated. This paper discusses how these regimes might be distinguished for the purposes of calculating HDR resources. Downward continuation of heat flow is likely to be a useful technique.

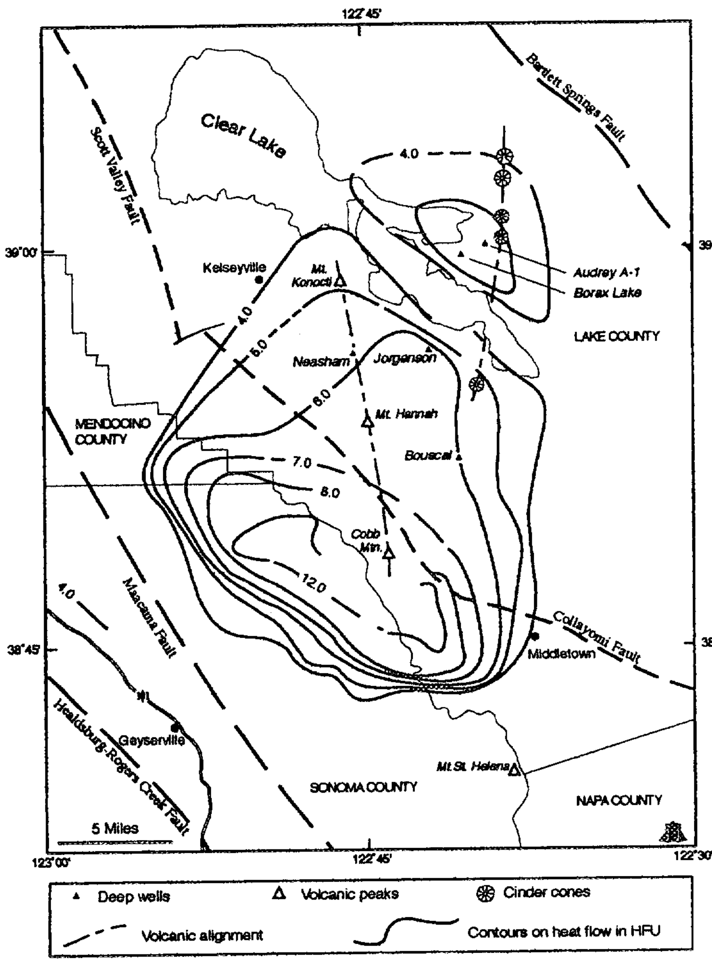


Figure 1: Generalized heat flow in The Geysers - Clear Lake area. From Burns (1996).

Heat Flow in The Geysers-Clear Lake Area: The Geysers-Clear Lake geothermal area is a region of high heat flow in northern California. The area is shown in Figure 1, along with generalized contours on heat flow.

The heat flow is probably derived from a sheeted intrusive complex, ranging in composition from felsic to mafic, extending down to the base of the crust, with the top generally at a depth of about 7 km (Figure 2). The origin and properties of the complex in depth were reviewed by Burns et al.(1995).

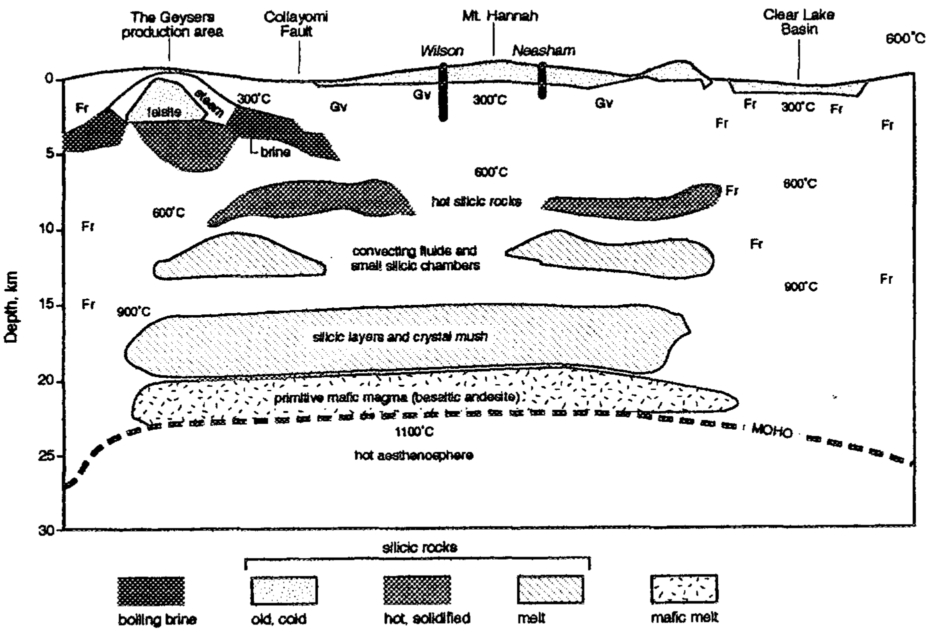


Figure 2: Diagrammatic cross-section of The Geysers-Clear Lake area. Modified by Burns (1996), from Stanley & Blakeley (1993).

Boundaries of the Conduction-Dominated Regime: The HDR resource is essentially the conduction-dominated regime in the roof rocks of the magmatic complex. However there is a question as to how to determine the boundaries.

We may infer the subsurface distribution of magma bodies from the surface manifestations of volcanism, such as lava flows, cinder cones, and effusive vents. When the observed distribution of volcanics is compared to the measured heat flow, the comparison shows that the heat flow is greater than 4 hfu over the magmatic complex, and outside that, drops to the background value of 1.5 to 2 hfu that is characteristic of the northern Coast Ranges. We adopt the 4 hfu heat flow value as the outer (low heat flow) boundary of the HDR resource, which is equivalent to selecting the roof rocks of the magmatic complex.

The Geysers steamfield lies within the geothermal anomaly of Figure 1, with convective heat flows ranging up to more than 12 hfu. When the distribution of producing steam wells is compared to the measured heat flow, the comparison shows that the heat flow over the steamfield is everywhere greater than 8 hfu. Accordingly we adopt the heat flow value of 8 hfu as the inner (high heat flow) boundary of the HDR resource.

The Hot Dry Rock resource at Clearlake is therefore, to a first approximation, an annular region bounded inwards at 8 hfu by The Geysers steamfield, and bounded outwards at 4 hfu by the outer edge of the magmatic complex.

Hot Dry Rock Resource Assessment: A four-step piecewise linear approximation gives the HDR power potential resource *Qhp* as 1.01E+21 J, which is equivalent to 2.78E+11 MWht. This is the quantity of heat in the rock above a temperature of 150°C and at a depth less than 5 km if cooled to 90°C. The volumetric specific heat was taken as 2.72E+6 J/m3. *Qhp* per unit area of the HDR resource at Clearlake is estimated to be about 20 times the average for the conterminous United States.

HETEROGENEOUS RESOURCE

However, this estimate assumes the resource is homogeneous and fails to take account of punctuation by zones of hydrothermal activity, particularly rows of fault-controlled hot springs (Figure 3). A more precise evaluation requires determination of the boundaries of the hydrothermal zones in depth.

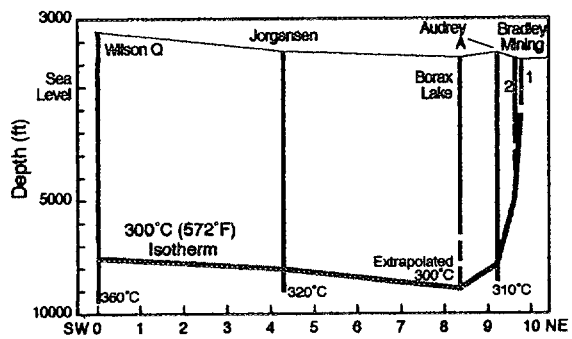


Figure 3: Cross-section of a hydrothermal zone punctuating a conduction - dominated regime.. Isotherms rise steeply to the Sulphur Bank hot spring at the right side of this section.

A reason for subtracting hydrothermal zones from the resource is that the Fenton Hill HDR system operates at an over-pressure relative to its environment, and that production system requires low impedance in the surrounding country rock in order to contain that pressure and to throttle leakoff. The HDR resource in California is not composed of uniformly impermeable rock but is punctuated by active dilating faults and zones of fracturing that offer low impedance pathways to the surface. Low-pressure zones that might vent to the surface must be either sealed off or avoided.

Downward Continuation of heat flow: The geophysical technique of downward continuation of heat flow introduced by Brott, Blackwell and Morgan (1979) for use in hydrothermal prospecting The technique might be very useful in site selection for HDR, for detection and avoidance of potential leakage zones.

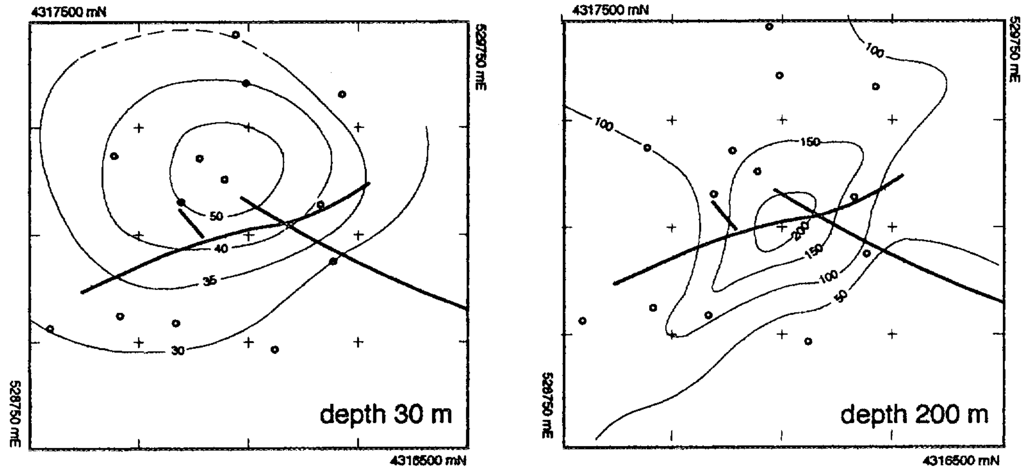
We are testing the technique at several scales in The Geysers - Clear Lake area. A small-area test is being made at the Sulphur Bank Hot spring, which will be close to any HDR system developed from the Audrey drilling pad. The results will be positive if the method enables us to safely avoid the spring, or identifies leakage zones hydraulically connected to the spring that should be grouted off during HDR reservoir construction.

Preliminary results are shown in Figures 4 and 5. We feel that this result determines the boundaries of the hydrothermal regime well enough for purposes of reserve estimation and site selection.

CONCLUSIONS

HDR resource assessments have treated continental shield areas a a homogeneous resource. The HDR resource in The Geysers-Clear Lake area is the roof rock overlying a wide magmatic complex, and a homogeneous model is appropriate as a first approximation.

However the resource is punctuated by steamfields and zones of hot spring hydrothermal activity, which need to be excluded from the HDR production resource.



Figures 4 & 5: Maps of the temperature at two depths for the hot spot at Sulphur Bank hot spring. Figure 4 (left) is the temperature field at a depth of 30 m observed by Beall (1985). Figure 5 (right) shows the temperature field determined by downward continuation at a depth of 200 m.

We are testing the downward continuation methods of Brott, Blackwell and Morgan as a means of determining the boundaries in depth between conductive and hydrothermal regimes. The results obtained so far are encouraging, as shown in one example from the Sulphur Bank mine.

The high heat flows make Pacific Rim rocks attractive for geothermal development. Leaky, active fault zones will not be a bar to HDR development provided that we can find them. This technique shows promise for site investigations in these rocks.

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GEOTHERMAL ENERGY DEVELOPMENT POSSIBILITIES IN ARMENIA

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The main way to overcome the present energy crisis in Armenia is the development of indigenous energy sources including geothermal energy. Due to young volcanic activity, the territory of Armenia is very promising for commercial use of geothermal energy, especially by hot dry rock systems.

The most interesting site is at Jermaghbyur, which was discovered by an exploration program targeting geothermal systems. These studies began in 1984 and were part of a comprehensive Armenian geothermal investigation project. As it is shown on the chart, at Jermaghbyur, a 1,000 m deep well was drilled; the measured temperature at 920 m was 99° C. The well intersects andesite-basalt, weathered and unchanged gabbro-syenite with highly crushed zones. The thermal gradient in the lower part of the well was 15° C per 100 m, showing a distinct trend of temperature increase with depth.

The conditions seem to suggest the presence of a cooling magmatic chamber with an estimated temperature of 250-300° C, at 2-2.5 km depth. The geothermal fields outline dimensions are 5x6 km.

The exploration program was stopped after the collapse of the USSR.

At present we conduct researches in optimization of the main parameters for development of geothermal deposits, including hot dry rock systems. The objective of the researches is to develop a technique that will allow to determine, by means of a perceptible graphical-and-analytical method, the values of parameters such as drilling volumes, quantity of generated electric power, specific cost per production unit, as well as justified boundaries of a deposit.

The obtained values of the indicated geological, technical and economic parameters will be optimal and mutually matching. It is also necessary to create the modern and flexible legislation base which is goal-oriented for attracting foreign investments.

POTENTIALITY OF 40 HDR SYSTEMS DETECTED IN MEXICO. A PRELIMINARY EVALUATION

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At the beginning of the next century, the sources of non-conventional energy, such as the systems in dry and hot rock (HDRS), will acquire larger technical and economic feasibility. These natural systems are an alternate source of energy, viable, non-pollutant and having an enormous potential. Their future use at worldwide level will only be limited by their location and punctual capacity. In Mexico, the preliminary potential that represents the hot dry rock for the energy resources of this country, was recently estimated. Forty different zones were identified as having possibilities of containing this natural resource beneath the surface (Fig. 1). For each one, its characteristics, seismic and volcanic risks, geological, geophysical, geochemical studies and existent drilled wells in the area, were defined . Figure 1 indicates the feasibility of each zone. Preliminary calculations allow to estimate that the HDRS potential of those regions, represents an amount of energy equivalent to 60 000 MW_e in hot rock for human benefit (Alonso, F., 1993).

Figure 1 shows that some HDR zones are wide regions within the national territory, for example the Neovolcanic Belt (1). Others are only punctual zones, but their characteristics make them attractive for the continuation of the exploratory studies. Eleven zones were detected and classified as having high possibilities for HDRS development. Another fourteen zones have intermediate possibilities and nine zones were classified as zones with low possibilities. Lastly, there are another six HDR zones whose feasibility is ignored because of the shortage of available information. The HDR projects would be applicable in Mexico to the development of balanced growth of many places close to HDR sites; from urban centers to rural communities, and industrial, agricultural and touristic developments. Their application is especially useful in the electrification of remote and isolated rural zones. The development of HDR resources could be carried out in integral form: using it in high enthalpy and direct cycles for electric power production, in low enthalpy and in binary cycles. It could also be used for the development of diverse civil engineering projects and in a multiplicity of applications that directly require heat as a primary source of energy.

From the analysis of costs of a HDR project, compared with the equivalent costs of projects based on other sources of energy, it was determined that the probable generation cost is about 13.20 US¢/Kwh [= u]. The HDR plants could still not compete with the majority of electric current plants. However, they turn out to be cheaper than the solar photovoltaic plants (20 u) and the plants based on turbogas-diesel (13.91 u); although still a little above the costs of the solar thermal (10 u) and the turbogas-gas (9.07 u) plants. Due to the great necessities of the country for electric and thermal power, the market for the exploitation of HDRS is wide open. The benefits from these systems could be significantly larger than the benefits offered by traditional geothermal energy.

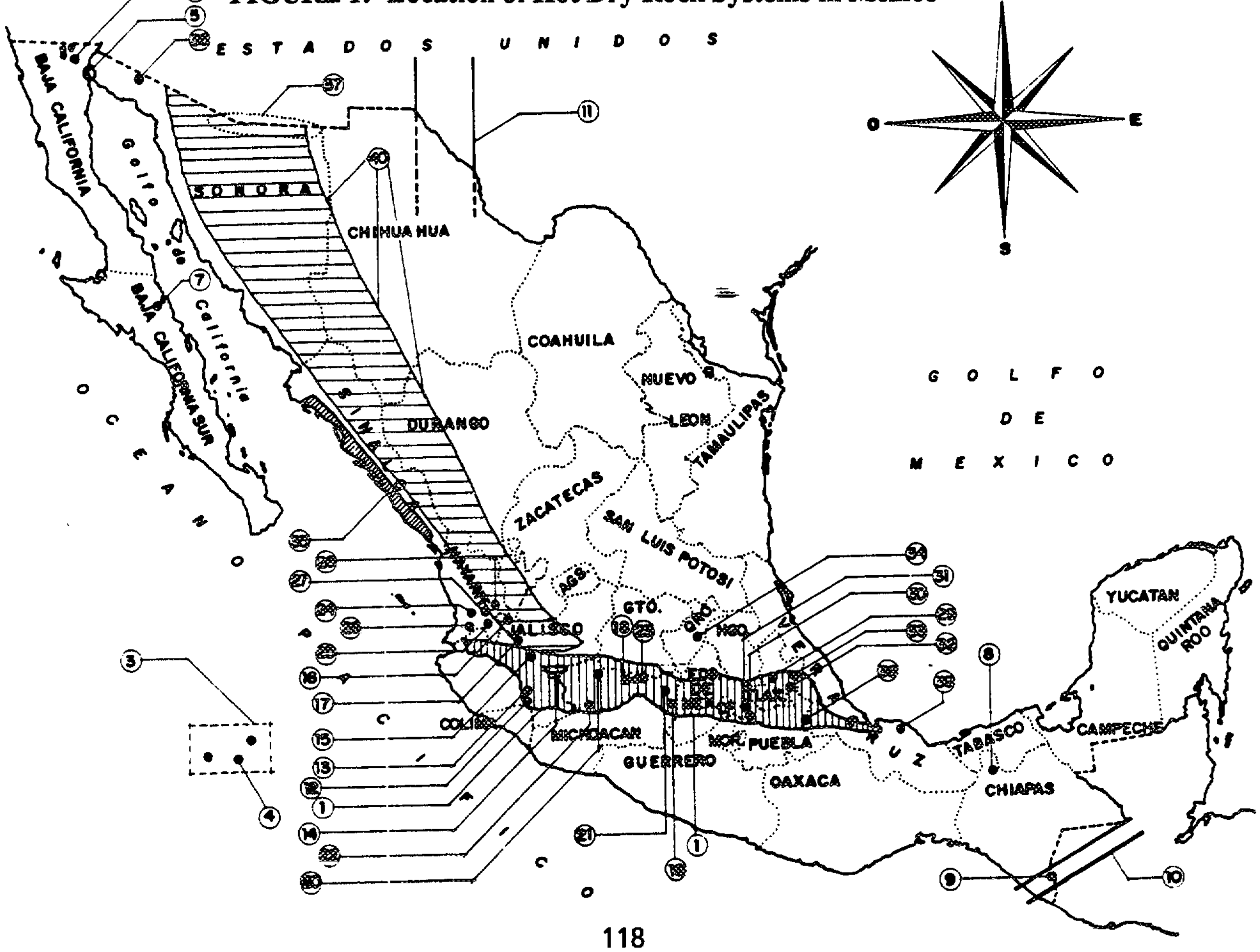
REFERENCE

Alonso, F. (1993). "*Sistemas Geotérmicos de Roca Seca y Caliente: Una Fuente de Energia No Convencional*". National Autonomous University of Mexico (UNAM), M. Sc. thesis, 215 pp., (101 references on the subject).

TABLE 1.- Classification of Hot Dry Rock Zones in Mexico

Zone with High Possibilities	LOCATION	Medium Possibilities	LOCATION
✪ All active volcanoes	- Several regions	★ Polochic-Motahua [10]	- Chiapas
✪ Mexican Volcanic Belt [1]	- Several States	★ Tequila [17] & Chapala [14]	- Jalisco
✪ Las Tres Vírgenes [7]	- Baja California	★ Jorullo [20]	- Michoacán
✪ El Chichonal [8] & Tacaná [9]	- Chiapas	★ Sanganguey [26],	- Nayarit
✪ Volcán de Fuego [12],		★ San Juan [27] and	
✪ La Primavera [15]	- Jalisco	★ San Pedro Lagunilla [28]	
✪ La Soledad [16]		★ Iztacíhuatl [30] -Popocatépetl [31]	- Puebla
✪ Los Azufres [21]	- Michoacán	★ Pinacate [36]	- Sonora
✪ El Ceboruco [24]	- Nayarit	★ Pico de Orizaba [38] and	
✪ Las Derrumbadas [32] and		★ Los Tuxtlas [39]	- Veracruz
✪ Los Humeros [33]	- Puebla	★ Río Grande's Rift [11]	-Coah./Chih.
Zones with Low Possibilities	**LOCATION**	**Unknown**	**LOCATION**
✳ Delta [5] & Laguna Salada [6]	- Baja California	❑ Revillagigedo Islands [3]	-Islands in the
✳ Nevado de Colima [13]	- Jalisco	❑ Volcán Evermann [4]	Pacific Ocean
✳ Araró [18], Paricutín [22] &	- Michoacán	❑ Domos de Zitácuaro [19]	- Michoacán
✳ Lago de Cuitzeo zone [23]		❑ Cráter Sta. María del Oro [24]	- Nayarit
✳ Amealco [34]	- Querétaro	❑ Caldera de Acoculco [29]	- Puebla
✳ a portion of the coast [35]	- Sinaloa	❑ Border bt. Sonora [37] & USA	- Sonora
✳ Western Sierra Madre [40]	- several zones		

FIGURE 1.- Location of Hot Dry Rock Systems in Mexico



Hard Rock Drilling Using High-Speed Type PDC Bits

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1. Introduction

We have been developed polycrystalline diamond compact (PDC) bits for hard rock drilling. These studies are classified into two groups; the development of core bits and the development of full-face bits. This paper describes results of drilling tests conducted to develop both type bits.

2. Results of field tests using PDC core bits

Shown in Fig.1 are PDC core bits with 8-15/32 in. O.D. and 4 in. I.D. used for field tests. The tests were conducted in wells called HDR-2 and HDR-3 located in Hijiori HDR test site. Rock drilled in the tests was granodiorite with the uniaxial compressive strength of about 118 MPa. The test results are summarized in Table 1. We successfully conducted field drilling tests, and it became clear that the PDC core bits can be applied to geothermal well drilling.

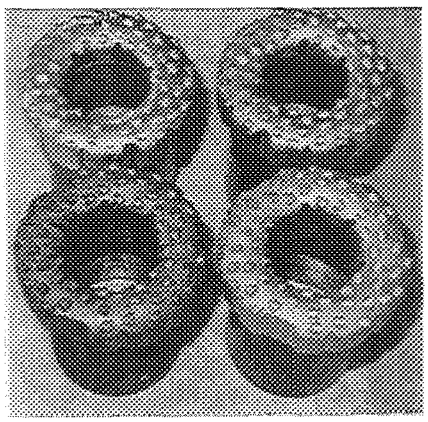

Table 1 Summary of coring results at Hijiori HDR test site.

Run No.	Depth(m)	Length(m)	Rate(m/hr)	Recovery(%)
1(HDR-2)	1905-1909.9	4.90	0.82	90
2(HDR-3)	1627-1629.34	2.34	0.43	88
3(HDR-3)	1641-1646	5.00	0.67	93
4(HDR-3)	1716-1721.04	5.04	0.56	89
5(HDR-3)	1755-1759.28	4.28	0.35	96
6(HDR-3)	1902-1907	5.00	0.42	88

← Fig.1 PDC core bits with 8-15/32 in. O.D. and 4 in. I.D.

3. Results of laboratory tests using PDC full-face bits

The field tests using the core bits resulted in successful hard granodiorite coring as mentioned above, but the development of PDC full-face bits for geothermal well drilling remained as the next challenge. Therefore, we started the study to develop full-face bits with high drilling efficiency. One of methods to improve drilling efficiency may be to use PDC bits for downhole motor drilling. These bits might be needed to be fabricated so as to rotate at high speed, since downhole motors usually rotate at about 150 to 400 rpm. Both decreasing of cutter diameter and increasing of cutter numbers set on a bit body are ideas to develop PDC full-face bits for downhole motor drilling.

Figure 2 shows 3-7/8 in. PDC full-face bits with different cutter diameters and cutter numbers. One example of the test results is shown in Fig.3. From the results of the tests, it became clear that the bits with cutters of 5.0 to 8.2 mm-dia perform better than those with cutters of 10.8 to 13.3 mm-dia in hard granite drilling at higher rotary speed such as 300 rpm and 400 rpm.

We have plan to develop PDC full-face bits with a diameter of 8-1/2 in. for downhole motor drilling during the last stage of this study. As a course in this development, we started testing bits with an intermediate diameter between 3-7/8 and 8-1/2 inches. PDC full-face bits with a diameter of 5-5/8 in. shown in Fig.4 were fabricated, based on the test results aforementioned. Figure 5 is an example of the test results. These bits could successfully drill through medium-hard to hard rock at the rotary speed of 250 to 400 rpm.

4. Conclusions

From the results of drilling tests using the PDC full-face bits with a diameter of 5-5/8 in., we get a prospect of fabricating high-speed type PDC full-face bits. The next subject of this study is to improve the durability of the bits in hard rock drilling such as granite.

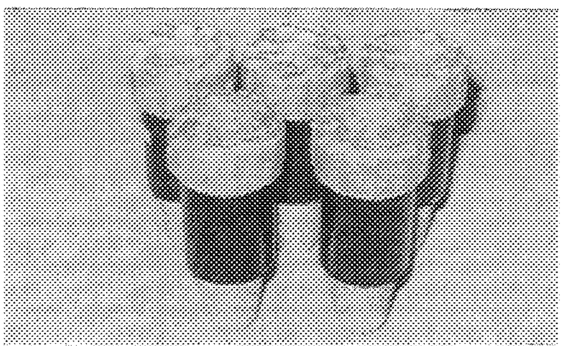

Fig.2 PDC full-face bits with diameter of 3-7/8 in.

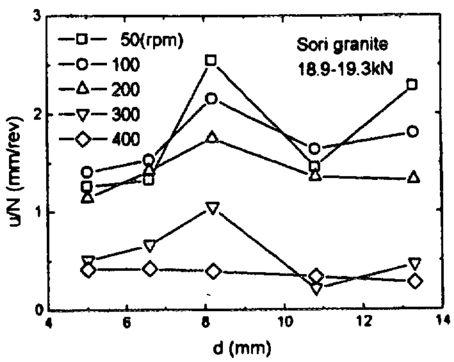

Fig.3 Relation between cutter dia. (d) and drilled length per revolution (u/N).

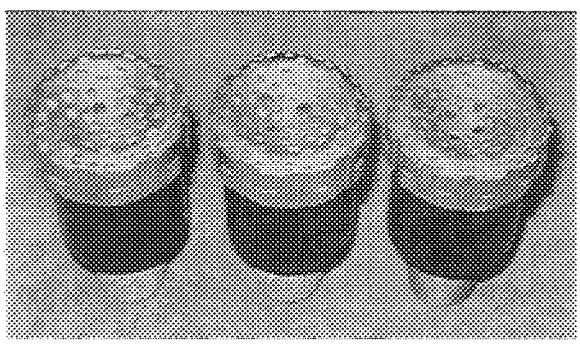

Fig.4 PDC full-face bits with diameter of 5-5/8 in.

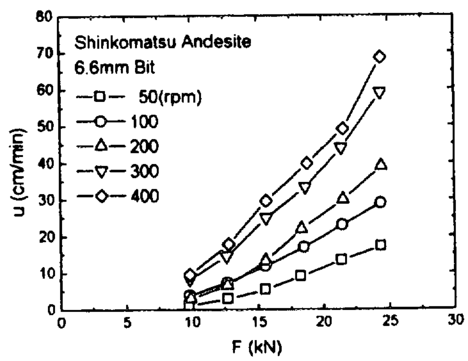

Fig.5 Relation between bit weight (F) and penetration rate (u).

Geothermal Heat Mining By Controlled Natural Convection Water Flow In Hot Dry Rock For Electric Power Generation

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ABSTRACT

This paper represents a novel method by which the thermal energy in hot dry rock might be transferred to a multiple set of water-filled pipe loops radially disposed about a large central riser connected to the radial loops at top and bottom. The down-flowing water in the radial loops, which reach far out from the central riser, gathers heat from the rock strata as it descends, reaching maximum temperature at the bottom where the central riser gathers all of the down-flow from the radial loops. The riser then delivers this water to the surface by natural convection circulation caused by the hydraulic head difference between the colder down-flow water and the hotter up-flowing water, thus requiring no auxiliary pumping power. At the surface the thermal energy of the water is transferred to a steam power cycle, either directly by flashed steam or through a heat exchanger. The water thus cooled then enters the down-flowing loops by a ring-manifold at the top for another heat gathering circuit. To account for draw-down in the rock temperature the return down-flow to the radial loops may be cycled, especially at low night time demand, to allow for heat recovery in this rock.

1. WELLHEAD DESIGN

The group of wells show in figure 1, described as the Shulman Star Heat Mining Concept, consists of several injection wells (downers) and one production well (riser). The unique feature of this concept is the large area for heat transfer available from the widely dispersed rock area which is gathered to one production well in the center for delivery to the power plant.

The production well is drilled directly downward to the 20,000 ft. depth and a 12 in. ID casing is cemented and heavily insulated in place from the surface to within 60 ft. from the bottom. This space will be used as a target into which the injection wells will be drilled. Three injection wells located in the circle near the production well at the surface, are directionally drilled to a 12,500 ft. depth at a distance away from the production well and then continued directionally to intercept the 60 ft. space at the bottom of the production well or riser. The injection wells have an 8 in. ID casing cemented in place to a depth allowing a continuous flow of water into the riser.

Gravity carries the higher density cool water (237°F) exhausting form the power plant to the lower depth of the injection wells where it is heated by the hot rock to a lower density. This lighter water is then propelled to the surface by the pressure differential imposed on the riser by the heavier down-coming water. Thus, with this convection flow, heat from the lower rock is brought to the surface for conversion to electric power.

As the heat in the rock area is drawn down, each injection well may be shut down for a period of time, or cycled, to recover heat by conduction from adjacent hot rock. During this period the remaining injection wells continue producing the convection flow in the riser. The ability of these wells to recharge with heat over time will determine the number of injection wells required in an area at a specific geothermal gradient for sustained power generation.

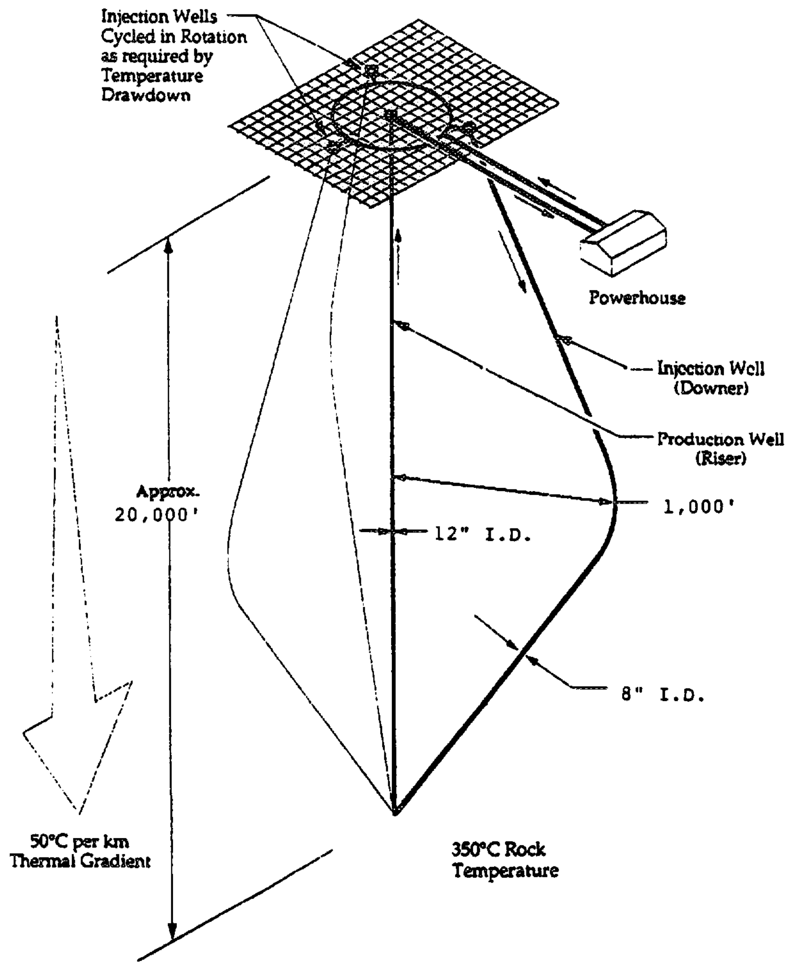


Figure 1.
SHULMAN STAR HEAT MINING CONCEPT

2. HEAT MINING PLANT DESCRIPTION

We have selected a 50°C/km geothermal gradient for initial design analysis of a commercial Heat Mining Power Plant to produce 11 MWe. This type of high gradient area should make sustainable operation more likely with existing drilling hardware. However, in this regard, the development of directionally drilling tools must be improved to work with the higher temperatures expected.

The process flow diagram of the 11 MWe Heat Mining Power Plant is shown in figure 2 and the following relates to that diagram.

Starting with Point 1 at the wellhead of the production well we find a steam and water mixture at 870 psia, 527°F. The two phase flow then passes through a throttle valve at Point 2 which controls the pressure to 80 psia and the temperature to 527°F in the separator at Point 3. The separated steam enters the turbine at Point 4 at 75 psia, dry saturated, with a mass flow of 200,000 lbs/hr to generate 11 MWe with an exhaust of 2.5 in Hga into the condenser at Point 5. This condensate at 105°F is pumped from the hot well at Point 6 to Point 7 where it is joined by water from the separator at a mass flow of 351,250 lbs/hr, 312°F.

To begin the heat mining, the combined condensate and separated water with a mass flow of 551,250 lbs/hr, 80 psia and a temperature of 237°F, now enters two of the injection wells at Point 8. The water flow then continues through the hot rock to Point 9 at 20,000 ft. depth. This water at 7,125 psia, 630°F now rises by convection to Point 10 where steam begins to flash at a well depth of 4,900 ft., 1,600 psia, 605°F. The steam formation creates an additional lift to deliver the two phase flow to Point 1 to then repeat the cycle. In this manner the heat is mined from the hot rock at depth and delivered to the surface by convection and steam lift without auxiliary pumping assistance for conversion to electric power.

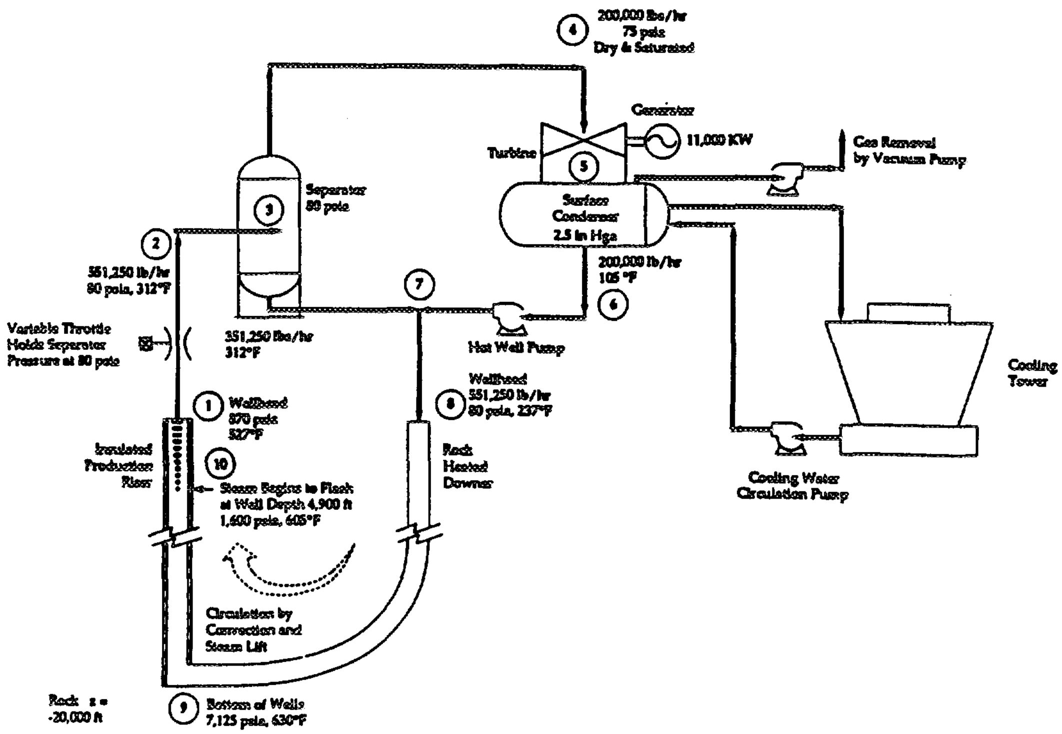


Figure 2.
FLOW DIAGRAM 11.0 MW HEAT MINING PLANT

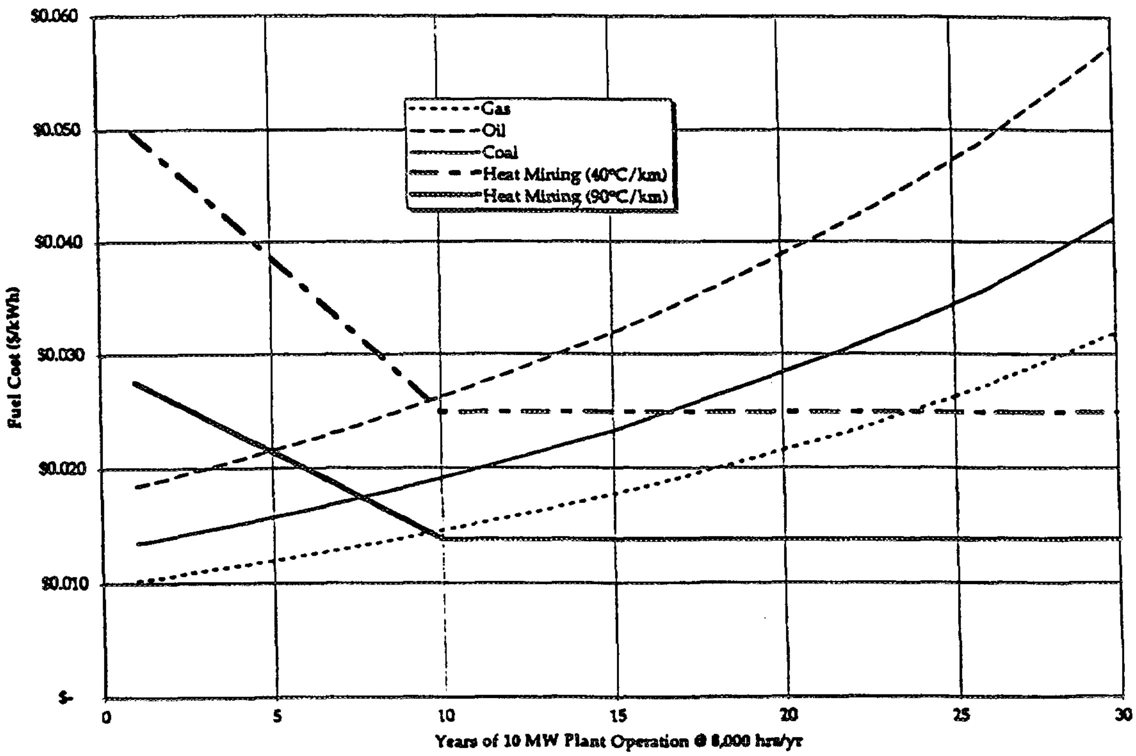
3. ECONOMIC FACTORS

In order for heat mining to become accepted in the commercial world for power generation, it must produce electricity at a cost competitive with fossil fuels. The chart in figure 3. indicates the present cost of the fossil fuels, gas, oil, and coal, for power generation and also indicates with a 4% inflation factor the cost of these fuels thirty years from now. If the Department of Energy through NADET can reduce the cost of drilling by 50%, which is their present target, in the next ten years, then the cost of heat mined energy with 40°C/km wells and 90°C/km wells will both produce power at a cost lower than the fossil fuels.

Fuel Cost per Kilowatt-hour

	Year 1	Year 5	Year 10	Year 15	Year 20	Year 25	Year 30
Gas	0.0102	0.0120	0.0146	0.0177	0.0216	0.0262	0.0319
Oil	0.0184	0.0216	0.0262	0.0319	0.0388	0.0472	0.0575
Coal	0.0135	0.0158	0.0192	0.0233	0.0284	0.0345	0.0420
Heat Mining (90°C/km)	0.0275	0.0214	0.0138	0.0138	0.0138	0.0138	0.0138
Heat Mining (40°C/km)	0.0497	0.0387	0.0249	0.0249	0.0249	0.0249	0.0249

Fuel Price Comparison



Inflation		4%
Number of Wells		4
Cost of 40°C/km Well	$	10,000,000
Cost of 90°C/km Well	$	5,000,000
Initial Interest Cost	$	4,800,000
Interest Rate		8%
Term of Loan		30 yrs

Gas Price Today	$	1.50	per million BTU's
Oil Price Today	$	2.70	per million BTU's
Coal Price Today	$	1.50	per million BTU's

Gas Conversion E.	50%
Oil Conversion Efficiency	50%
Coal Conversion Efficiency	38%

Figure 3.

4. CONCLUSION

In the future Hot Dry Rock can serve as a nation's largest source of electric power, available in all regions of the world. Given the enormous size and indigenous nature of deep crustal heat, a serious development effort must be made for its conversion by heat mining to power generation by government funding on a par with nuclear development.

At the present time several hundred thousand tons of low sulphur coal are being transported every day from western regions of the USA to eastern USA power plants, approximately 1,500 miles in order to comply with environmental regulations for SO_2 discharge to the atmosphere. There is no doubt that the 5 to 10 miles envisioned in geothermal heat mining would involve a great deal less effort and cost to attain this environmental objective. The advent of deeper drilling to reach heat productive zones in the lower crust will also produce greater heat exchange surface, so that these deeper wells will be even more suitable for heat mining.

Presented in this paper is one possible solution which should be verified by a test program of convection cells drilled and piped into hot dry rock. Development of deep drilling techniques into high temperature rock must also receive near term government funding. With major funding for this development there is no question that we can put in place a natural geothermal heat mining system that will be one of the great achievements of the twentieth century.

Heat Mining in Salt Domes

S. J. Altschuler

Production of oil and gas depends on the occurrence of several contingencies:- the presence of hydrocarbons, a geologic trap at an accessible depth, and rock sufficiently porous that the hydrocarbons can accumulate in the trap. Conventional production of geothermal energy by mining fluids also requires several contingencies:- the presence of hot rock, water at an accessible depth, and rock sufficiently porous that both can come into contact. Heat mining requires only one contingency:- hot rock which can be accessed. The objective is to eliminate the contingencies required so that geothermal energy becomes an engineer's game rather than a geologist's.

In principle, if one goes deep enough, sufficiently hot rock is reached and any location is as good as any other. Unfortunately, drilling technology is not advanced enough to make the ideal of such universal accessibility economically feasible.

The properties of salt:- high thermal conductivity, plasticity, and occurrence in large, deeply penetrating structures (salt domes) offer a chance for a compromise between the above ideal and reality.

Salt dome geology is well known. Salt domes are large structures which can be detected by a variety of means. The upthrusting of salt domes from the base salt layer warps strata and creates traps in which oil can collect. Dome boundaries are often marked by wells drilled to find such traps. The Louann salt, the base layer for Gulf Coast salt domes, is believed to lie 40,000 to 55,000 ft below the surface.

If a double pipe heat exchanger could be inserted into a dome to the base salt, the relatively high thermal conductivity of salt (3 to 5 times that of rock) and an average geothermal gradient (2°F/100 ft) would provide useful amounts of energy. This is to be accomplished by sinking a single closed end well and fitting it with an insulated open ended inner pipe. The major factor determining well output (aside from the average geothermal gradient) is the depth which can be reached. Well output varies roughly as the square of the depth. Both the heat exchange area and the temperature difference available for heat transfer between the salt and the well pipe which forms the outer wall of the double pipe heat exchanger are proportional to depth. The nominal output is 3/4, 1-1/2, and 3 MWe for depths of 30, 40, or 55,000 ft for well lifetimes of at least 40 years.

Heat transfer from the salt to the well is by conduction. The thermal conductivity of the salt varies inversely as the absolute temperature. Since thermal conductivity is not a constant, the equations are nonlinear and cannot be solved in closed form. A computer model allows the variation of output and other parameters with time to be readily calculated. Further simplification is gotten if two phase flow is avoided by maintaining sufficient pressure at the well outlet.

A closed system has several advantages:

The working fluid does not come into contact with the strata so there is no need to dispose of dissolved solids or noncondensable gases such as carbon dioxide or hydrogen sulfide. The system is environmentally clean.

The optimum working fluid can be chosen for a given set of conditions. Because of the limited cross-sectional area available to provide for two flow paths, insulation, and pipe walls, there is a strong predisposition to chose the fluid with the maximum heat capacity per unit volume. However, there are other properties considered:- critical temperature, critical pressure, viscosity, density, toxicity, and cost. The availability of an equation of state for the working fluid which can be incorporated into the computer model is also desirable.

The efficiency of converting heat to electricity can be improved so that this value approaches that of ordinary thermal power plants. This can be done by using feedwater heating. Preliminary calculations for a nonoptimized case show that although well power output decreases, the lifetime is extended so that the power output integrated over time is increased several percent even without correcting for the increased efficiency as a Carnot cycle is more closely approximated.

Other methods of improving efficiency and output are available which can only be attempted with closed systems.

The heat energy in salt domes is a finite resource. Given the original temperature distribution, the lifetime (defined as ending when well outlet temperature drops below 300°F) depends upon the demands on the well and the volume of salt allocated to it. The former depends on the mass flow rate of the working fluid (primarily) and the well inlet temperature; the latter by the number of wells per unit area. As a first approximation (based on a few rough calculations), well lifetime is inversely proportional to the number of wells per unit area. However, more detailed calculations may show that there is an optimum number of wells per unit area which results in more complete and efficient mining of the available heat.

Operations can be conducted so as to maximize either cash flow (i.e. immediate electrical output) or the total electrical output from the resource. The former will require as many wells as can be financed to spread out the up front costs of the lease and take advantage of any economies of scale for the generating equipment. There will be no feedwater heating and mass flow rate will be optimized to provide maximum electrical production from the current temperature distribution. To maximize the total electrical output, there will either have to be an optimum number of wells or some decision as to the desired lifetime of the resource. Feedwater heating and other methods of increasing resource efficiency will be employed as will varying the mass flow rate to maximize electrical output over the chosen resource lifetime.

Extrapolating from the calculations which have been made, 1,000 square miles of salt domes could provide 1,500 quads (10^{15} Btu) of electrical energy. This is comparable to the 2,400 quads of electrical energy obtainable from the world's proven reserves of either oil or gas. It is eight times the amount available from the current value of the U.S. proven reserves of oil <u>and</u> gas. The Bay Marchand massif alone (admittedly the largest single collection of domes) is over 300 square miles.

Hot Dry Rock and the U.S. Geological Survey
A Question of Priorities

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During the past quarter-century, the United States Geological Survey (USGS) has made significant contributions in the field of geothermal energy. These include resource assessments, regional geologic, hydrologic and geophysical studies, and site-specific investigations of areas of possible commercial geothermal interest. Until recently, however, specific contributions to Hot Dry Rock (HDR) have been limited to service on advisory panels, the provision of data related to individual projects, and perspectives on the hot-dry-rock resource base in conductive environments.

The enactment of Public Law 102-486, the Energy Policy Act of 1992, saw the assignment of definite responsibilities relating to HDR to the USGS "in consultation with the Secretary of Energy". This mandate provided some explicit guidelines and individual tasks in areas where the USGS already had close ties to the Department of Energy and a number of its National Laboratories. The most immediate task (Section 2502) was the hosting of a workshop on the potential of HDR in the eastern United States. The workshop was held in Philadelphia, PA, on February 15, 1993, in conjunction with a workshop on "Potential of HDR Resources for the U.S. Electric Utility Industry" hosted by the Electric Power Research Institute (EPRI). The report to Congress of the workshop was released as USGS Open File Report 93-377, in November of 1993. Its principal findings can best be summarized by quoting from the abstract of the Report:

> For the purposes of the workshop, the eastern U.S. was defined as those states from the Great Plains to the eastern seaboard. Within this region, heat mining is presently restricted to geothermal heat pumps (as demand-side management), spas and a few demonstration projects for space/process heat. Under present economic and technological constraints, mining heat for electrical power generation is not feasible in the eastern United States. Given a modest boost in electrical rates, power generation from hydrothermal sources might prove economic in two or three regions of unusually high surface heat flow. Outstanding technical barriers to the development of HDR heat mining in the east turn primarily on the issues of drilling costs and the general applicability of the hydrofracturing technology to compressional stress fields typical of upper crustal rocks in the East. The public's acceptance of geothermal heat pumps suggests that if these technical barriers can be overcome, HDR can, indeed, provide a substantial proportion of the energy needed in the next century.

Section 2501 of the Act instructed the USGS to establish a "cooperative Government-private sector program with respect to hot dry rock geothermal energy resources on public lands". The mandate was broad, encompassing resource assessment and classification, field testing of processes and techniques, and development and dissemination of technical information. The USGS was also empowered to "enter into contracts and cooperative agreements with any private or public entity to carry out additional projects with respect to the utilization of hot dry rock geothermal energy resources".

The initial response to section 2501 comprised the establishment of a "Heat Mining Studies" project and the completion of a "Public Issues in Earth Sciences Circular (1125)" titled "Tapping the Earth's Natural Heat" (Duffield et al., 1994). The Heat Mining Studies Project conducted a reconnaissance of operating hydrothermal power plants in the Great Basin of the western United States. Senior scientists of the Geothermal Research Program also drafted an initiative for augmented funding to accomplish the objectives set out in the Energy Policy Act of 1992.

From the outset, it was recognized that the USGS could not carry out a comprehensive, independent research program in HDR without an unrealistic expansion of its research and support staff. On the other hand, some redeployment of existing geological, geophysical and hydrological expertise, and expansion of established collaborations with colleagues in universities and DOE National Laboratories was deemed both feasible and desirable. Such actions could provide productive new research avenues in the course of implementing the mandate of P.L. 102-486, even without additional funding. A decision was made to revisit the Basin and Range Province, with a particular view to identifying both topics and geographic areas suitable for HDR research.

The consensus view of USGS researchers embodies the philosophy of Garnish et al. (1992) and more recently, Ledingham (1995) that "An HDR system is any geothermal system where [re]injection is necessary to extract heat at a commercial rate for a prolonged period". By this view, HDR is not a unique, stand-alone technology, but is an end member of a spectrum of field situations defined primarily by in situ permeability (Figure 1). The domain labeled "suitable for reservoir enhancement" in Figure 1 represents a huge resource within which the technology developed at Fenton Hill and elsewhere can be deployed in incremental fashion to enhance the productivity of existing hydrothermal reservoirs and to bring prospects that are not presently commercial into production. The establishment of partnerships among USGS, other government, university, and industry researchers has been the goal of USGS outreach related to the mandates of the Energy Policy Act of 1992 (see, eg., Sass, 1995) with particular emphasis on the Great Basin.

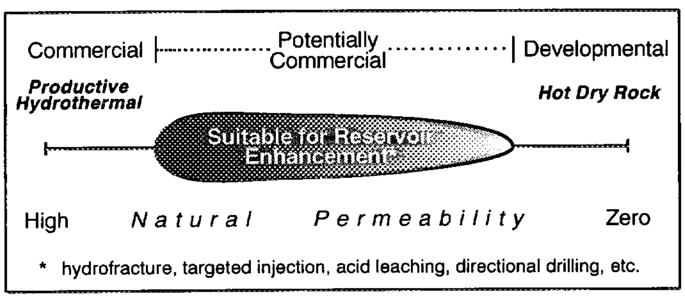

Figure 1. *Diagram illustrating the permeability fields for commercial, potentially commercial and developmental geothermal reservoir technology.*

A promising start has been made at Dixie Valley (DV, figure 2) which is one of the most productive fields in the Great Basin, but within which there are areas of unexpectedly low permeability. Oxbow Geothermal Corporation, the operator and principal leaseholder has been generally successful and maintains a profitable operation, but of the 26 wells that have been completed, at least 7 can be classified as hot but dry holes. When redrills are counted, there are 18 dry "legs" of wells. A cooperative reservoir enhancement study among Oxbow, USGS and Stanford University grew out of the initial reconnaissance by the Heat-Mining Studies Project in August of 1994. The visit to Dixie Valley led to the USGS and Oxbow co-hosting a workshop in May of 1995. That workshop, which included a one-day field trip to Dixie Valley, reviewed the existing data on the thermal, hydrologic and structural regimes and led directly to a successful field experiment in a new geothermal production well drilled into the reservoir associated with the Stillwater fault zone in the autumn of 1995 (Hickman and Zoback, 1996; Barton et al., 1996). This study, which was funded jointly by Oxbow, the USGS and the Department of Energy, combined temperature, pressure, flowmeter and borehole televiewer logs together with hydraulic fracturing measurements of in situ stress to study the nature, distribution and hydraulic properties of fractures associated with the Stillwater fault zone. The orientations and magnitudes of the stresses in the well (73B-7) are such that the Stillwater and associated sub-parallel faults are in a state of incipient normal faulting. Also, analysis of fracture orientations and fluid-flow indicators demonstrate that the hydraulically conductive fractures are optimally oriented for frictional failure in the current stress field. Thus, the maximum permeability within the reservoir rocks at this site lies in the plane of the Stillwater fault. The study has continued with additional measurements in a redrill of an existing well and will be extended to some idle, non-productive wells later this year.

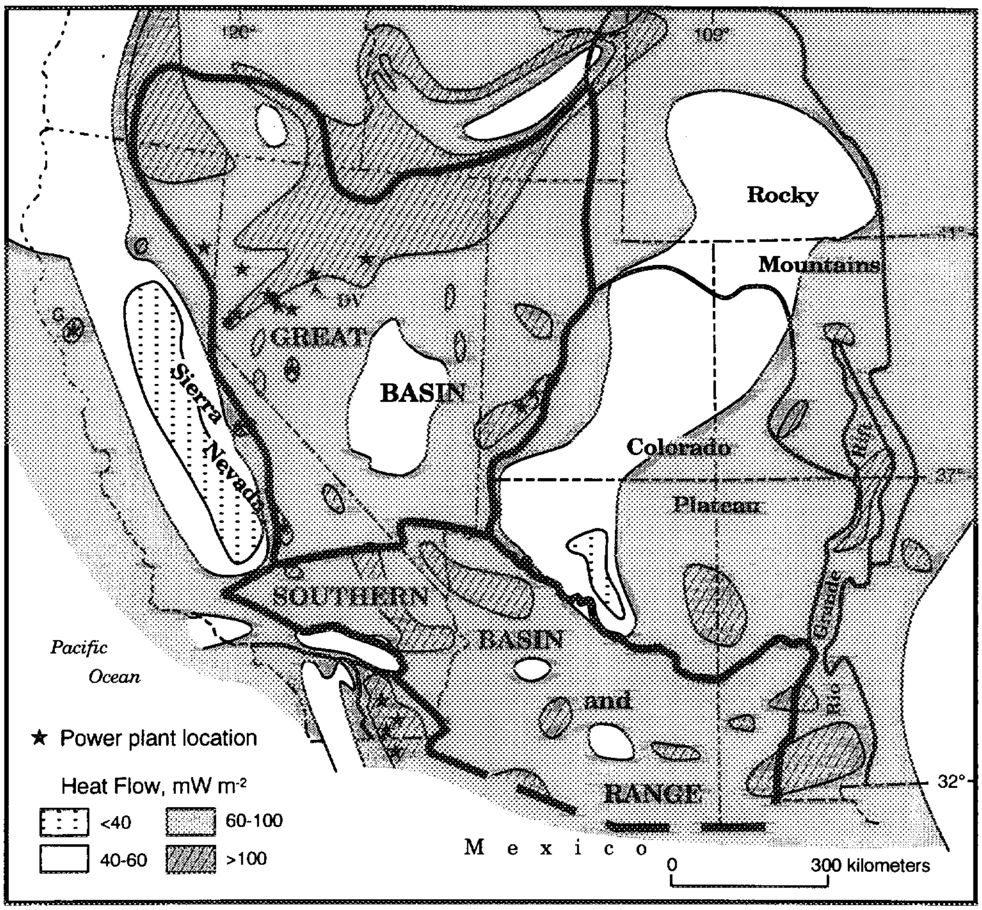

Figure 2. *Heat flow in the Basin and Range Province and surrounding terranes, together with locations of presently operating power plants.* ***DV****, Dixie Valley.*

Despite the favorable start at Dixie Valley, continued USGS involvement in HDR studies is threatened by a serious erosion of funding (Figure 3). The Geothermal Investigations Program was combined with the Volcano Hazards Program (VHP)in FY 1995. In the current fiscal year it became a component of the VHP and was cut by $1M. For FY 1997, an additional $2.5M cut to VHP (the ONLY cut in the entire FY'97 Geologic Division budget relative to the current year) will be absorbed completely by the geothermal component (the only "green" energy technology with which the USGS is involved) leaving a very small core activity (Figure 3). While this re-ordering of priorities within the USGS severely limits activities related to HDR and profoundly alters cooperative relations of long standing, we hope to obtain maximum leverage for our remaining support by continuing to work in partnership with DOE and interested industry groups. Perhaps in future years, a growing awareness of the importance of renewable and alternate energy sources will reverse the present trend.

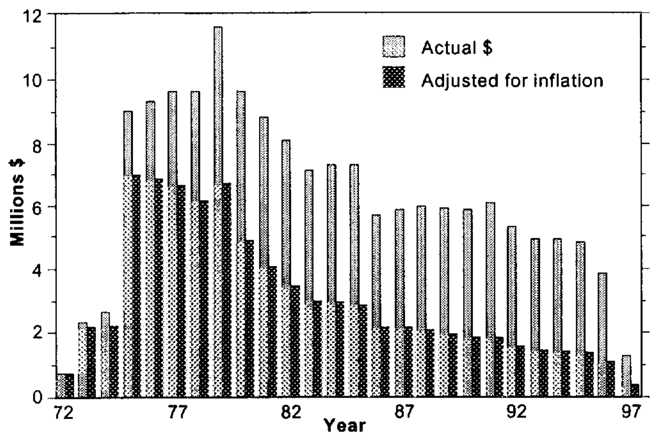

Figure 3. Funding history for USGS geothermal investigations. The numbers for fiscal year 1997 are requested.

Acknowledgements: I thank Wendell Duffield, Marianne Guffanti, Steve Hickman, Manuel Nathenson, and Patrick Muffler for their comments on the first draft.

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Ledingham, P. (1995), Hot Dry Rock Geothermal Energy - More Common than You Might Think, Nonrenewable Resources, 4, pp 296-302.

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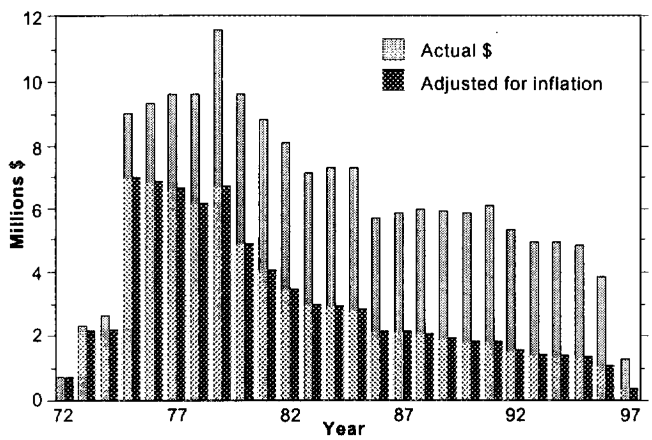

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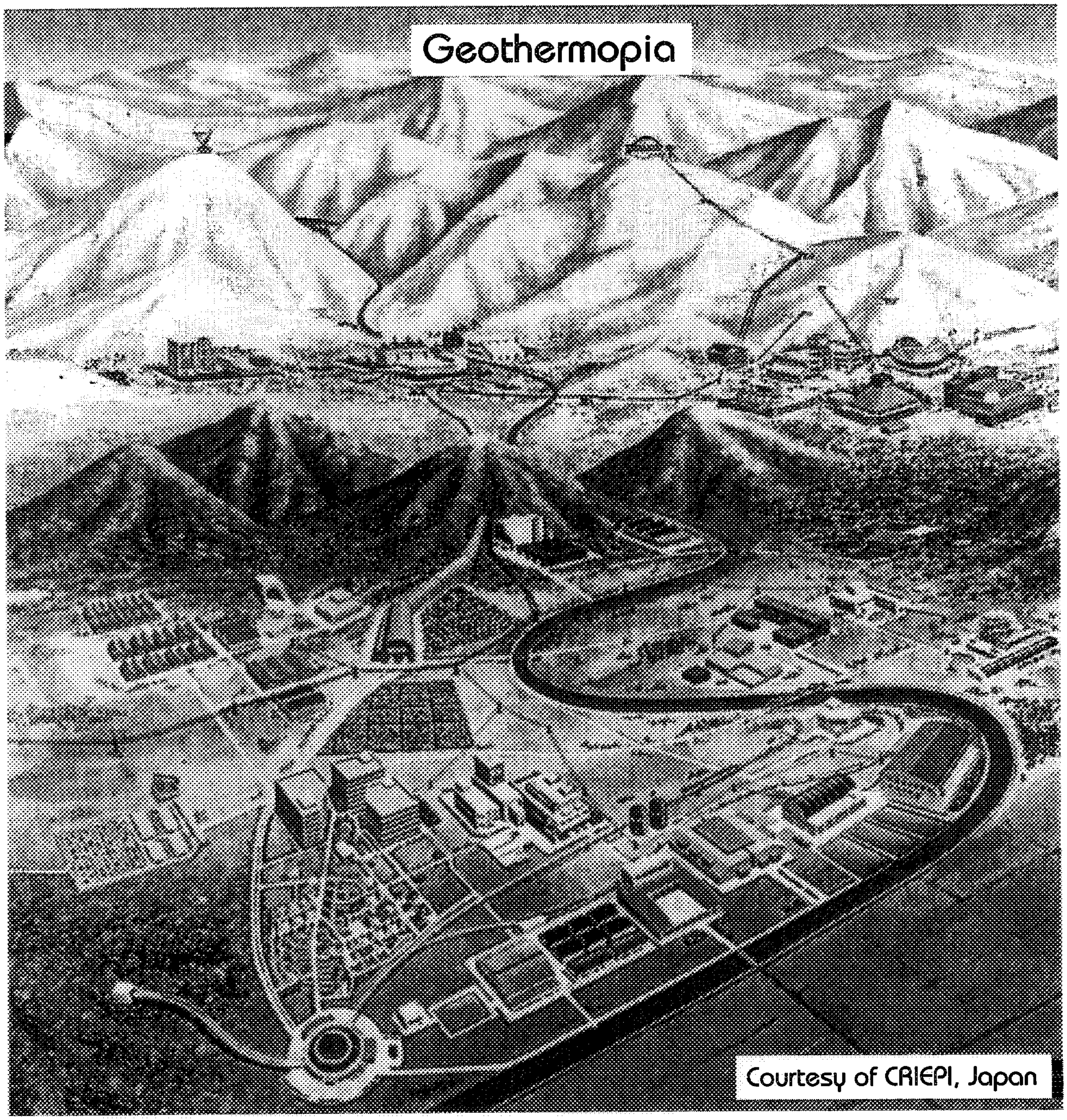
Session 10:
Town Hall – Future Directions

Session Chair: Dave Duchane



THIRD INTERNATIONAL HOT
DRY ROCK FORUM

Roger Peake
Geothermal Program
California Energy Commission

ABSTRACT: The California Energy Commission's Geothermal Program is an important part of the state's support of alternative energy resources development, and continues to provide a funding opportunity for a variety of geothermal efforts in the state.

The mission of the Geothermal Program is to promote research, development, demonstration, and commercialization of California's enormous earth energy heat sources. Through the Program, we support development of geothermal resources while protecting the environment and promoting energy independence. We provide financial and technical assistance, gather and disseminate geothermal information, and support policy development.

SUMMARY: Topics include a brief overview of the Geothermal Program and, as an example, how it has supported evaluation of the hot dry rock (HDR) potential in the Clear Lake area of northern California. And, a brief description is included about how the Commission, through the Geothermal Program, can support future HDR initiatives in the state.

Since 1981, the Geothermal Program and more than 60 public entities have co-invested approximately $124 million in about 160 geothermal projects in California. The Commission share of this total is about $31 million.

The primary source of funding for the Program is revenue paid to the United States Bureau of Land Management for geothermal leases on federal lands in California. In a typical budget year, about $2.0 million is provided to the Commission to fund geothermal projects. Currently, however, about $4.7 million is available.

The HDR evaluation in the Clear Lake area is a very important step forward in development of this technology and is an example of cooperative research efforts. With Department of Energy support, the Commission co-funded work of Los Alamos National Laboratory (Laboratory) staff through the City of Clearlake to evaluate the resource potential, and support transfer of the HDR technology developed at Fenton Hill, New Mexico to California.

In 1986, the Commission funded the Phase I evaluation. This was the first investigation of factors affecting HDR potential in the Geysers-Clear Lake region. The resulting information includes data on geophysics (including gravity, magnetics, and resistivity); geology; and heat flow with graphs and a portfolio of seven maps. The data confirmed exceptionally high heat flow in the region, ratified the geothermal potential, and suggested selected topics for further study.

Phase II, commenced in 1991, and sponsored by the Commission, adds considerably to the body of geologic knowledge in the Geysers-Clear Lake area. The HDR potential is further defined in six reports including 1) thermometry and heat flow, 2) geologic structure, 3) geohydrology, 4) seismicity, 5) geothermal regimes, and 6) surface water hydrology. Several of these technical reports have been published by the Laboratory, and the remainder including an Executive Summary are in final publishing stages.

Technical advances from a Clear Lake HDR initiative may result ultimately in tools and/or techniques for drilling in deeper and hotter environments, which could also benefit the domestic oil and gas industries. Advances in subsurface measurements and monitoring are likely to provide insights into the long-term behavior of geothermal reservoirs which could help extend the longevity of the declining steam reserves at The Geysers. The HDR investigation is focusing new light on the sub-surface geology in the area, and when fully understood, promises better understanding of the geothermal resource potential.

What happens next?

The Commission will continue a portfolio approach to funding geothermal projects that will move California towards greater energy security, and enhance the competitive position of geothermal energy uses. The Geothermal Program will continue to build research, technology transfer, and commercialization partnerships with private entities, government, and academia. Projects could include RD&D that results in new tools and techniques, and reduces operation and maintenance costs.

The Commission will continue to support the development of longer-term RD&D and expansion, for example, of geothermal heat pump uses in California. It will strive to build on past successes in the Clear Lake area to demonstrate the HDR technology in a non-Fenton Hill geologic environment.

An essential part of future HDR work in California will be the commitments of private financial and industrial partners to co-share the risks and costs of resource investigations and reservoir development. The Geothermal Program is committed to supporting these efforts in cooperative undertakings.

A continuing role for the Commission's Geothermal Program will be to foster HDR RD&D partnerships with academia, and public and private entities, to serve as a potential project funding source, and to disseminate information on HDR technical advances.

I invite inquiry for more information and to share dialogue on further work on a HDR project in the Clear Lake area or elsewhere in the state.

OPTIONS FOR A RESTRUCTURED HDR PROGRAM IN THE USA

Dave Duchane
Los Alamos National Laboratory

INTRODUCTION

Development of HDR technology in the United States took a dramatic turn in the fall of 1995 when the US Department of Energy canceled its solicitation for an industry-coupled project to produce and market energy derived from an HDR resource. In announcing the cancellation, the DOE stated:

> "Rather than pursue a commercialization goal, the Department will refocus the Geothermal Hot Dry Rock Program to work with industry and other interested parties to resolve the key technical issues. Los Alamos National Laboratory (LANL) is expected to play a continuing role in technology development."

The process of restructuring the US HDR program began with a meeting convened by the Geothermal Energy Association (GEA) at the offices of UNOCAL Geothermal Co. in Santa Rosa, CA in December 1995. At that meeting, geothermal industry representatives reviewed the HDR program, affirmed the importance of HDR to the future of geothermal energy, and developed a number of recommendations. It was suggested that HDR work be integrated into the conventional geothermal industry, that the Fenton Hill HDR site be mothballed, and that interactions with other HDR programs around the world be increased. The group did not develop specific goals for future HDR work, but recommended that another panel be convened to conduct an in-depth review and formulate short- and long-term goals for the geothermal industry, including the long-term commercialization of HDR.

Since announcing the restructuring of HDR, the USDOE has ordered the closure and complete decommissioning of the Fenton Hill HDR site. Dismantling all geothermal facilities at Fenton Hill is now underway. The DOE is now in the process of organizing a review of HDR by an independent panel to be convened under the auspices of the National Academy of Sciences. Concurrently, another GEA group is being organized to advise the DOE on HDR issues. As this paper is being written, however, no definitive course has been set for future HDR work in the United States. The following discussion suggests options for future HDR projects in the US that will more closely ally HDR with the conventional geothermal industry while at the same time maintaining the grand promise of HDR to transform geothermal energy from its current perceived status as a minor energy resource of strictly regional significance into a widely-recognized, world-class resource capable of making a major contribution to the world's energy needs in the 21st century.

OPTIONS FOR FUTURE HDR WORK IN THE USA

Industry-Coupled HDR Technology Applications. Cooperative Projects which apply HDR technology and expertise to the solution of hydrothermal problems and increase the productivity of hydrothermal or quasi-hydrothermal (hot wet rock) reservoirs have the potential to provide almost immediate benefits to the geothermal industry. During more than 20 years of work on HDR, unique capabilities in drilling, hydraulic fracturing, fracture location and characterization, reservoir engineering, logging tool design and application, fluid injection, tracers, and reservoir modeling have been developed. In some instances, especially in regard to drilling and logging-tool development, significant technology transfer has occurred via the service companies that have at times been involved in the HDR project. However, in other areas such as reservoir engineering, fracture mapping and characterization, reservoir modeling, fluid injection, and tracers, there has as yet been little effective technology transfer to the hydrothermal industry.

Examples of potential industry-coupled projects include the application of HDR reservoir fracture mapping techniques at hydrothermal sites to improve the efficiency of hydrothermal field development, the use of HDR injection experience to enhance the effectiveness of reinjection into hydrothermal reservoirs, and the extension of HDR reservoir modeling techniques to hydrothermal situations. Obviously, projects in any of these areas are worth pursuing only if they have the solid support of one or more industrial organizations and can potentially contribute to improving the technical competence and competitive status of the US geothermal industry.

HDR Niche Development Projects. The knowledge base accumulated during work at Fenton Hill should be applied to develop a new HDR site that may have practical as well as research and development applications. In view of the depressed price for electric power generation in the US, any such domestic HDR site must fit into either an especially attractive electricity niche (due to advantageous resource characteristics, the load-following potential of HDR systems, or local economic factors that lead to high electricity prices) or be located where there is an opportunity for a direct use application of the HDR energy. Direct use opportunities should be carefully evaluated and developed, as appropriate, in cooperation with private industry as well as state and local government entities that may have an interest in energy or economic development.

Given the current bleak outlook for the electricity market in those parts of the US where hydrothermal resources are found, niche applications of HDR may at present represent one of the few opportunities for additional geothermal development in the US. Finding a niche for HDR in today's highly competitive energy marketplace is a challenging task but, for all of the above reasons, it must be pursued if HDR and, indeed, the geothermal industry itself, is to have any chance of being a significant factor in the US energy picture of the future.

Increased International HDR Activities. HDR research and development has had an international flavor almost since its inception. The high point of international cooperation was reached during the period from 1980 to 1986 when Japan and Germany participated both financially and technically in the work to develop the large HDR reservoir at Fenton Hill. The international contacts made during those years have led to continued international cooperation in the form of periodic personnel exchanges and international meetings as evidenced, for example, by the 3rd International HDR Forum.

Efforts to increase international cooperation in geothermal energy via a new International Energy Agreement (IEA) have been underway for some time. The Japanese have taken the lead in the area of HDR and are proposing their New Energy and Industrial Development Organization (NEDO) be the operating agent for all HDR work conducted under the auspices of the IEA. Active participation by the US in IEA-sponsored programs will benefit all concerned. Other nations will be able to draw upon the large body of HDR knowledge that has been amassed over more than 20 years of work in the US, while, in turn, the US, with its field program now terminated, will have the opportunity to continue to play a role in the worldwide HDR development.

SUMMARY

Work at the Fenton Hill test site in northern New Mexico has taken HDR from the purely conceptual stage through a demonstration of the technical viability of exploiting this ubiquitous geothermal resource. Fenton Hill is now being closed and the US HDR program is being restructured. Options for future HDR work in the US include industry-coupled projects to apply HDR technology to the solution of problems faced by the hydrothermal industry, the pursuit of niche opportunities for HDR development and application, and an increased participation in international HDR cooperative projects.

A Scientific Pilot Plant
The next Phase of the development of HDR technology in Europe

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European research in the development of Hot Dry Rock technology to mine heat at great depths is concentrated at the Soultz site in France. The site is situated about 50 km north of Strasbourg in the Rhine Graben, which extends over 300 km and contains a known zone of 3000 km^2 with high surface heat flow caused by convective heat transfer via a deep partially permeable joint network.

It is considered that three phases of development will be required before this technology matures to the point of being a commercial proposition. These phases are the Scientific Reconnaissance, the Scientific Pilot Plant and the Industrial Prototype.

The Scientific Reconnaissance Phase (which is nearly completed) consists of the determination and evaluation of basic parameters at depth, the selection of the European site, the conceptual, and finally detailed design of the Scientific Pilot Plant. The present phase (the first phase) started in 1988 and will be completed towards the end of 1997. The second phase (see Fig. 1) is expected to start in 1998 and will take about 5 - 7 years to complete. The third phase could be configured for an industrial plant with a number of wells, generating electrical power in the range of 20 MWe.

The science/engineering results obtained during the reconnaissance phase to date have given sufficient confidence in the future of the technology to be able to proceed with the Scientific Pilot Phase. The next two years (1996-1997) will be used to obtain additional data to improve the technology, establish a prime contractor (an industrial consortium) and, after carrying out a conceptual design, to put forward a proposal to the funding agencies for the Scientific Pilot Plant.

The Scientific Pilot Plant is expected to cost around 50 MECU (over a period of 5 - 7 years, including essential generic research) and the majority of the funding is expected to be provided by France, Germany and the European Community. It is envisaged that the plant will consist of a three well module with one injector and a producer on either side equipped with downhole pumps. The injection flow will be around 80 l/s (1300 GPM) with the production flow of around 40 l/s (650 GPM) per well. It is proposed that the present deep well GPK2 could be deepened to about 4500 - 5000 m depth (15 000 - 16 500 ft) to obtain a reservoir temperature approaching 200°C. After the stimulation of GPK2, two additional deep wells will be drilled at about 500 m distance from GPK2 as production wells. Existing infrastructure will be reinforced and new facilities will be added.

In this phase, it is expected to obtain data and experience which will help in the planning and construction of the Industrial Prototype. This will include such items as thermal drawdown, improvement of the reservoir characteristics, validation of the reservoir diagnostic techniques, control of the effects of circulation on the geochemistry of the rock mass, control of corrosion, understanding and improvement of parameters which affects the economics of HDR. Within the scope of these activities a careful cost analysis of the HDR technology will be performed.

This Scientific Pilot Plant phase will be led by a prime contractor (an industrial consortium) who will be responsible for the management of the programme. Presently a legal entity is being formed by two regional utility companies; Electricité de Strasbourg (French) and Pfalzwerke (German). Three other organisations (Electricité de France, ENEL and RWE) have requested an option to join at a later date.

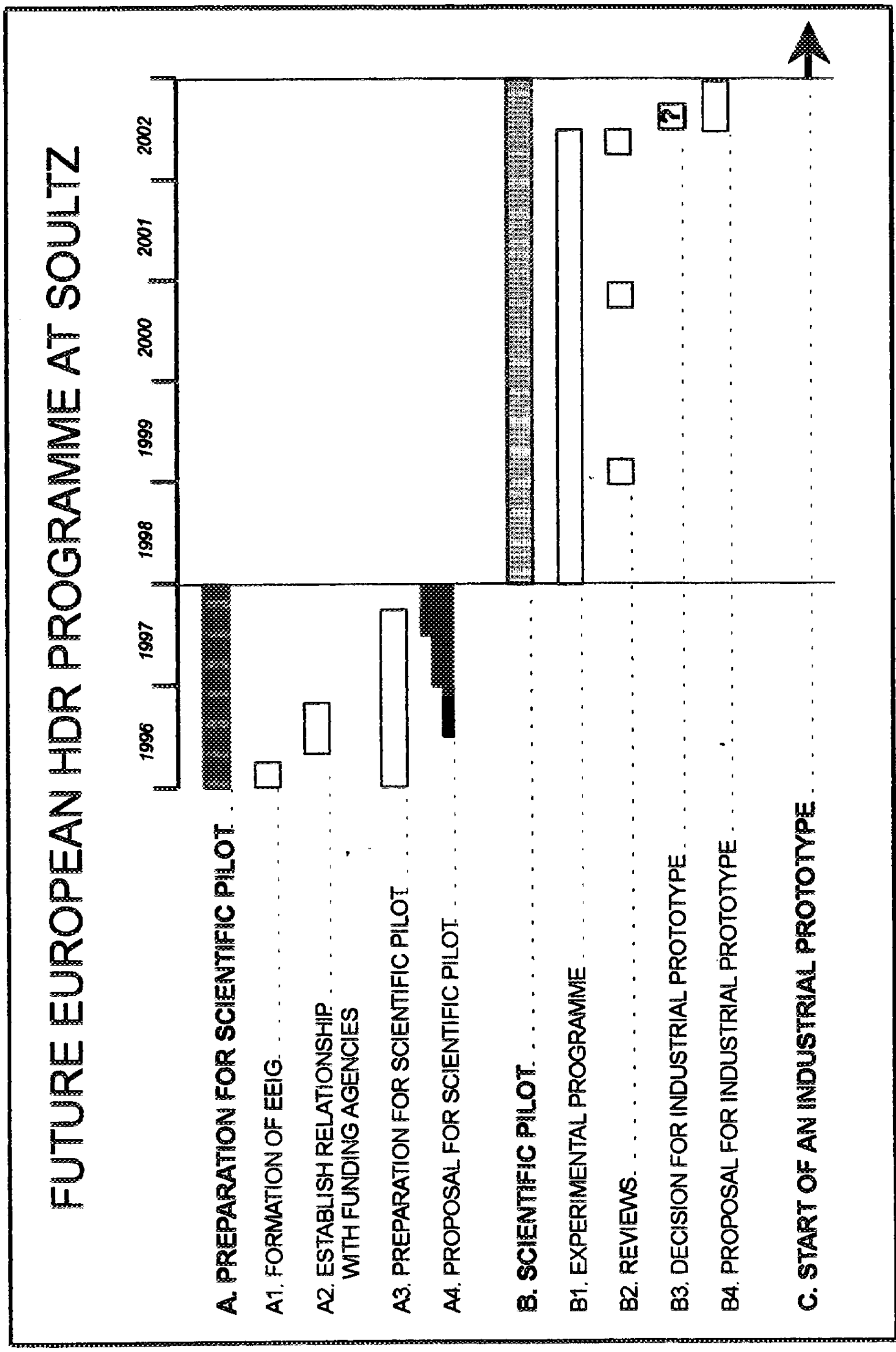

Figure 1

Program of the Hijiori HDR project and a path to a HDR power plant in Japan

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Overview of HDR Subsurface system at Hijiori

As shown in Table 1, Hijiori subsurface system consists of two reservoirs, an 1800-m-deep reservoir and a 2200-m-deep one, and four wells, SKG-2, HDR-1, HDR-2a and HDR-3. It has been created since 1985. During the creation steps year by year, the Hijiori project showed the following important for design of a HDR subsurface system.

1) Water flow through the reservoirs was dominated by natural fractures at the site.

2) A pair of production wells drilled at both sides of an injection well along the dominant flow direction was efficient to decrease water loss through the loose reservoirs at Hijiori.

3) The injection well at Hijiori is open to single reservoir. Because, an operation of multi fracturing is not easy, even outflow into each reservoir will not be expectable, nor control of each outflow will be nearly impossible. In addition, injection rate into a well is limited by its diameter. We think, multi reservoirs consisting of injection wells connected to single reservoir and production wells connected to all of the reservoirs will be realistic because of easy production control and less drilling cost.

Table 1 Reservoirs and wells connected to the reservoirs at Hijiori

Reservoir name	Injection well	Production wells
1800-m-deep reservoir	SKG-2 open from 1,788 to 1,802 m	HDR-2a * open from 1,510 to 2,302 m, and HDR-3 open from 1,516 to 2,303 m
2200-m-deep reservoir	HDR-1 open from 2,159 to 2,205 m	HDR-2a * open from 1,510 to 2,302 m, and HDR-3 open from 1,516 to 2,303 m

* In 1994, HDR-2 was plugged up to 1,600 m and deepened to 2,303 m. Thus its trajectory is different from the original. So, we changed its name as HDR-2a.

Plan of a two-year circulation test through the 2200-m-deep reservoir

During a preliminary circulation test of the 2200-m-deep reservoir in 1995, we got a promising result of the maximum apparent recovery rate of about 60 % at an injection rate of 17 l/s. It was produced from two production wells, thus, it is comparable to 80 % by three production wells during a three-month circulation of the 1800-m-deep reservoir in 1991. However, unexpected two phenomena were observed during the preliminary circulation.

The first was inflow into the production wells from the upper reservoir besides the deeper one. Thus real recovery rate of the deeper reservoir is less than the apparent one. Furthermore, PTS logging of the production well showed that the inflow from the each reservoir changed frequently even though the sum of the inflows measured at wellhead was nearly constant. The first phenomenon will be analized by relation between pressures of the reservoirs and pressures in the wells at the depths of the reservoirs. However, data acquired in 1995 was insufficient to analyze it.

The second was unstable production from HDR-3 observed during PTS logging in it and/or reducing opening of its wellhead valve, even though its well head pressure and wellhead temperature were nearly same as those of HDR-2a. By PTS logging of HDR-3, depth of flushing point in it became deeper during PTS logging and/or reducing valve opening.

In 1996, we will conduct a one-month circulation mainly between HDR-1 and HDR-3. It is expected that impedance between the wells will reduce during the circulation. In addition, several PTS log operations will be done in HDR-1, HDR-2 and HDR-3 for getting data to analyze especially the relation between the pressures of the reservoirs and those in the wells.

We have a plan of a two-year circulation test of the 2200-m-deep reservoir from the autumn in 1999 till the autumn in 2001. Two years of 1997 and 1998 will be spent for preparation of the two-year circulation. During the test, we will measure the following data: 1) thermal withdraw of the reservoir; 2) change of reservoir volume with time; 3) thermal withdraw of each fracture in the reservoir; 4) change of flow rate of each fracture with time. Main objective of the circulation is to estimate life and volume of the 2200-m-deep reservoir. In addition, we expect to reconfirm the promising results got by LTFT at Fenton Hill such as, thermal stability, increasing rock access, low water consumption, benign geochemistry and so on (Duchane, 1995).

Path to a HDR power plant

If we will obtain the promising results by the two-year circulation, a plan of a HDR demonstration plant will be made. Prior to it, we have discussed proper size of a HDR power plant in Japan from reservoir potential and power generation cost.

Capacities of hydrothermal plants in Japan are from 10 to 50 MW. In addition, water supply at usual Japanese geothermal area in mountains is limited. Thus, some tens MW will be realistic plant capacity of a HDR power plant in Japan. However, an estimated cost of a supposed 30 MW HDR plant, as shown in Table 2, is about twice of unit cost of nuclear or thermal power plant in Japan. Thus, until the end of the two-year circulation, we will study measures to reduce the cost to not higher than 15 Yen/kWh of smaller hydropower plants in Japan.

Table 2 Cost estimation of HDR power plant in Japan

Plant capacity (MW)	Unit cost averaged for 15 years (Yen/kWh)	Estimated by
3	36	NEDO
10	34	NEDO
30	22	NEDO
75	18	CRIEPI
240	13	CRIEPI

The competitive generation cost of a HDR plant will be accomplished by lowering construction cost of subsurface system, lowering operation cost, shortening lead time and so on. Thus, we will study the following: 1) subsurface design for fewer injection wells, fewer production wells, fewer stimulating operations, less water loss and less injection pressure; 2) production technology for stable production, less thermal withdraw, less scaling and fewer operators; 3) Planning of heat mining from a HDR body. In addition, we will study to find a best demonstration site, including study of the meaning of the best.

On the other hand, it will be possible in Japan to construct a small HDR plant in a small volcanic island, because unit cost of a diesel generator used in a small island is comparable to the estimated cost of supposed 30 MW HDR plant. In addition, water will be able to be made by condensing steam.

Another way is utilizing dry wells at hydrothermal power plants as HWR concept proposed by Takahashi and Hashida.

Conclusion

At present, the main objective of the Hijiori HDR project is to succeed the two-year circulation through the 2200-m-deep reservoir that will be conducted from the autumn in 1999. In addition, by the end of the circulation, we will study the measures to reduce gentian cost of a HDR power plant and the best site for the first demonstration plant. If we will get promising results by the circulation, we will be able to proceed to a planning of a HDR demonstration plant.

The plan will be discussed with the Director for Development Program of Renewable Energy of the Agency of Industrial Science and Technology (AIST) of the Ministry of International Trade and Industry (MITI), the National Institute for Resources and Environment (NIRE), and the Committee on HDR R&D Program of NEDO chaired by Prof. Abé. Furthermore, international collaboration is vital for our project.

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MTC PROJECT: INTERNATIONAL COLLABORATION TO DEVELOP NEW MICROSEISMIC MAPPING/IMAGING TECHNIQUES FOR DEEP GEOTHERMAL ENERGY EXTRACTION

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Sendai 980-77, Japan

ABSTRACT

An understanding of geothermal reservoir structure is essential for modern deep geothermal reservoir development. It is generally accepted that only Acoustic Emission (AE) and Micro Seismic (MS) techniques are practical for deep geothermal reservoir imaging. However, the images observed usually show a "cloud" of locations and allow only a hazy estimate of the location and size of the reservoir. These techniques provide insufficient information about reservoir structure, orientation and probable hydraulic behavior.

Various research groups have recently developed new AE/MS mapping techniques that yield new images and hopefully a better understanding of the geothermal reservoir. These research groups made an agreement in late 1993 for international collaboration to test the new techniques, and an international project, termed the "MTC-Project" (MTC: More Than Cloud), was launched. The project is funded for three years from FY1995 by NEDO (New Energy and Industrial Technology Development Organization, Japan) as an International Joint Research project and for three years from FY1996 by MESSC (Ministry of Education, Science, Sports and Culture). 10 research groups are now involved, with a total of 27 researchers; these groups are shown in Table 1. There are 24 research programs using data sets from 8 fields, as shown in Table 2 and Figure-1.

This international effort is a purely scientific and academic project, with the aim of improving such techniques and to advance geothermal technology. The project involves cooperative research, with exchange and utilization of the field data sets obtained by each research group, which are usually obtained at significant cost to individual groups. Reports relating to advanced AE/MS mapping techniques, and suggestions for developing better understanding among members, will be presented at regular project meetings. It is expected that more universal technologies will be established by verifying and applying the shared data to different geothermal fields and among participants using different measurement systems. Additionally, the understanding of individual reservoirs in each field will be improved. The data gathered and the techniques developed during this project will play an important role in further development and operation of geothermal systems.

Table 1: Members of the MTC-Project.

group leader	affiliation
M. Fehler	New Mexico Tech., USA
A. Green	CSM Associates, UK
R. Baria	Socomine, France
H. Niitsuma	Tohoku Univ., JPN
K. Hayashi	Tohoku Univ., JPN
H. Kaieda	CRIEPI, JPN
K. Tezuka	JAPEX, JPN
H. Itoh	Geological Survey JPN
T. Wallroth	Charmes Univ., Sweden
F. Cornet	IPGP, France

Table 2: Research program in MTC Project.

Field	Reservoir characterization	Analysis of crack behavior	Doublet analysis	Collapsing method	Hypocenter tomography	AE reflection method	Seismic while drilling
Cornwall, UK			O	done			
Soultz, F	O		O	O	O	O	O
Fenton Hill, US				O	O	O	
Clinton, US			O				
Ogachi, J	O		O	O	O		O
Hijiori, J			O	O			
Kakkonda, J						O	
Hachimantai, J							O
Fjallback, SW							
Fundamentals		O	O		O	O	O

O : under way

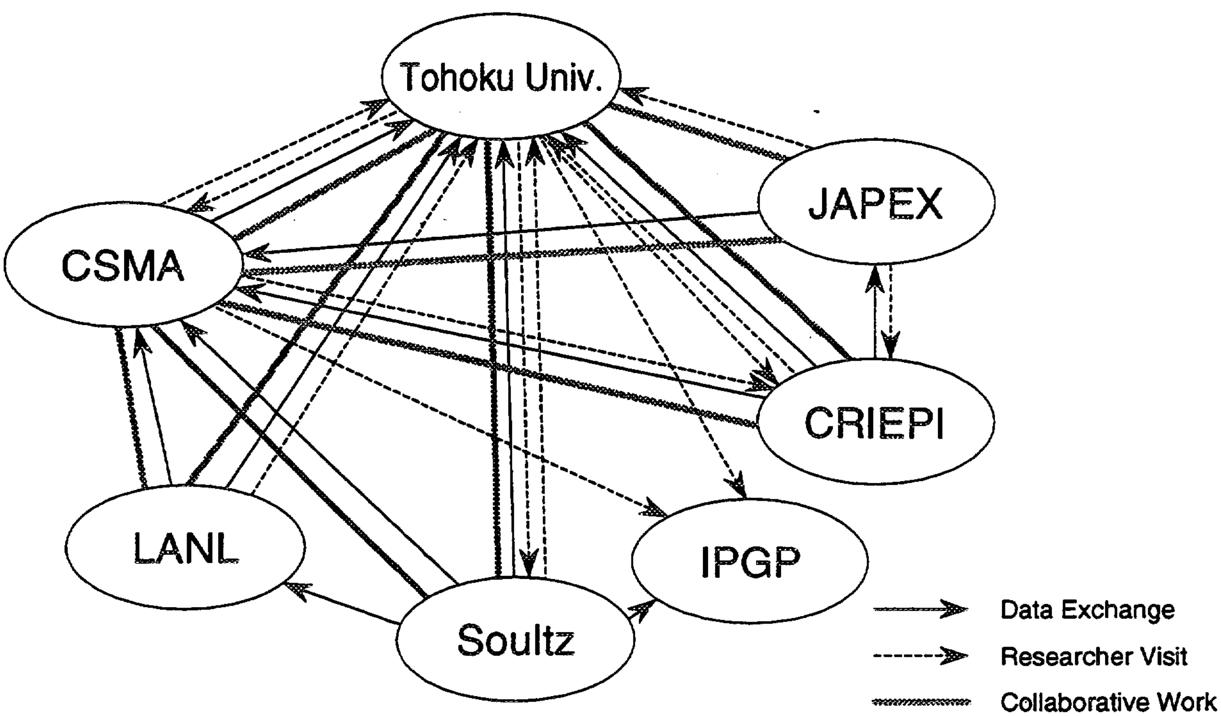

Figure-1: Activities of the MTC Project in FY1995

3rd International HDR Forum, Santa Fe, New Mexico USA
May 13-16, 1996

Title: Objectives of the HDR Academic Review, Sendai, Japan, March 1997

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It is now 13 years since the first major academic meetings on HDR/HWR[1] were held in Japan[2]. In view of the many demonstration projects since that time, we feel that it is now time to take stock of the progress that has been made world-wide. With this in mind we propose to organize a conference, in the form of a structured scientific / academic review, to be held in Sendai, Japan. Following the presentation of papers, the conference will follow a workshop format designed to produce a 'science and technology map'. The map will identify those technologies and design paradigms which have been sufficiently developed for application to commercial scale HDR / HWR operations, and those which require further development or fundamental research.

Rationale

Since the last reviews in Japan in 1982 a number of large scale field trials of HDR/HWR circulation have been carried out. The data gathered from these experiments, together with increasing knowledge of the subsurface environment from deep drilling projects has strongly affected the way that we think about the possibilities of heat extraction from low permeability basement rocks.

Within the context of identifying future research priorities, both in Japan and world-wide, this process of "paradigm realignment" needs to be made explicit and we need to renew the research map first drawn by *Abé et al.* [1982] in 1982. We hope that the academic review of HDR/HWR to be held in Sendai, Japan in March 1997 will meet that need.

The view in 1982

A review of the content of the published papers from the 1982 meetings shows the major areas of interest:

- Hydraulic fracturing / fracture mechanics theory
- Overviews of experiments at shallow depths
- Single or multiple fracture heat transfer models
- Stress field determination
- Location of microseismicity
- Borehole logging (thermal, flow, fractures, velocities)
- Large scale hydraulic fracture data interpretation
- Thermal fracturing
- Interaction of hydraulic and natural fractures

Although the topics of the meetings emphasized hydraulic fracturing and fracture mechanics approaches, it is clear that the importance of the existing natural fracture network and of shear movement on these fractures as being important or even dominant processes in the creation of engineered geothermal reservoirs had not yet emerged.

Certain comments, in retrospect, appear to presage the development of thinking over the next decade e.g.,

"The proper method of growing more than one crack on a single borehole would be to grow the cracks sequentially so that only one crack at a time is active. All cracks that are intended to be inactive would have to be sealed to prevent their further growth", *Nemet-Nasser* [1982, p29] which anticipates ideas of multiple stimulations from the same hole;

"Probably a crack by hydraulic fracturing will discontinuously extend connecting large pre-existing natural fractures scattered in the formations. It is estimated that the volume change caused by the connection will be the reason of the abrupt well-head pressure change observed....", *Nakatsuka et al.*, [1982,p106], anticipating the linkage of borehole hydraulic fractures to the natural fracture system in HWR systems;

"... it may be concluded that where two fault systems intersect with high angles only one of the fault systems will be a breeding fault of geothermal fluids under certain stress fields, so that only one of them is of interest for geothermal exploration.", *Hayashi and Yamasaki* [1992, p.341] anticipating the heterogeneity of flow in natural fracture systems and that this might be stress controlled.

The role of natural fractures in stopping hydraulic fracture propagation was recognized both in theory and practice, e.g.,

"When a reservoir intersects a joint, an opening of reservoir occurs at the juncture through separation and slip on the surface of the joint", *Abé and Sekine* [1982, p450];

"...heavy dye residue of the fluid occurred several meters away from the point of intersection where the hydraulic fracture crossed the fault or the natural fractures, suggesting that these discontinuities were inflated during pumping and hydraulic fracture growth. Consequently, in highly fractured regions the hydraulic fracture was not a single plane, but a zone with multiple strands.", *Teufel and Warpinski* [1982, p. 258].

The lack of emphasis on the importance of the natural fracture systems probably stemmed from the widely held belief that the natural fracture frequency decreased exponentially with depth, although information was becoming available which contradicted this view, e.g.,

"...typical of all the wells we have investigated in that the fracture density decreases only moderately with depth. This is completely unlike the anticipated rapid decrease of fracture density with depth suggested by Snow (1968).", *Zoback* [1982, p 205].

Objectives of the review

The remit of the review will be the characterization, creation and operation of HDR/HWR reservoirs based on work carried out since the last review conducted in Japan at the end of 1982. It will exclude specific discussion of drilling technology and surface plant. These technologies are driven by technical and economic developments in hydrocarbon and conventional geothermal exploitation and form part of the constraints within which HDR/HWR research is being conducted. Also excluded is specific discussion of HDR economics although, of course, HDR reservoir design targets are essentially economic in nature. The main objective of the review is to provide a "research map" which will guide HDR/HWR research funding agencies in prioritizing future work.

The review will attempt to address the following points:

- To review world progress in HDR/HWR projects
- To identify those coherent groups of ideas that have proved successful in describing and engineering HDR/HWR reservoirs, and those less successful
- To review progress in the component technologies (hardware and software) that have proved or seem likely to be necessary for HDR/HWR exploitation (i.e. constraining technologies)
- To clarify, in respect of each of the various applicable technologies and ideas, how far we are along the learning curve
- To identify new or neglected problems
- To produce a research map for HDR/HWR

Organization

The organization of the working groups reflects the need for both specialist input related to specific scientific or engineering techniques and for the integration of the results of these methods into coherent methodologies for field characterization of the subsurface environment, the creation of an adequate thermal and heat exchange reservoir and for the management of this reservoir during operation.

Nine working groups have been identified, Figure 1. Five research specialist groups cover:

- Geology / Geochemistry / Prospecting
- Rock Mechanics / Stress Measurement
- Seismics / Borehole Measurements
- Hydraulics and Well Testing
- Modeling and Numerical Analysis

Each of these groups will report on their specialist areas on the state of the art and research priorities for the three phases of HDR/HWR development and exploitation mentioned above.

There will be a scientific overview group for each phase charged with making an integrated picture of the present and possible future research results, and identifying research synergies from the different specialist areas. They will also pose some identified problems to the scientific specialists with the intention of trying to generate ideas for new research activities.

The three overview groups will present their reports to the "system integration" group who will review their content and consolidate them into a single report identifying the research priorities for the next decade.

Footnotes

[1] In Japan HDR is defined as the extraction of heat from low permeability rocks possessing no significant natural fractures and HWR as the exploitation of geothermal heat by modification of the existing, but low permeability, natural fracture system.

[2] First Japan-United states Joint Seminar on Hydraulic Fracturing and Geothermal Energy (Tokyo, Japan, November 2-5, 1982) and Symposium on Fracture Mechanics Approach to Hydraulic Fracturing and Geothermal Energy (Sendai, Japan, November 8-9, 1982), *Nemat-Nasser et al.*, [1983]

System Integration:	Overall System Design		
Scientific Overview: / Scientific Methods:	Field Characterization	Fracture / Reservoir Creation	Circulation and Heat Extraction
Geology / Geochemistry / Prospecting	●	●	●
Rock Mechanics / Stress Measurement	●	●	●
Seismics / Borehole Measurements	●	●	●
Hydraulics and Well Testing	●	●	●
Modeling and Numerical Analysis	●	●	●

Figure 1. Organization of working groups for the HDR Academic Review to be held in Sendai, Japan, March 1997.

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Proposed IEA Implementing Agreement on Hot Dry Rock

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Introduction:

It is now about 20 years since the first HDR geothermal energy system was completed at Fenton Hill in 1977. Since then a number of projects such as Fenton Hill, Rosemanowes, Soultz, Hijiori, Ogachi, etc. have been developed throughout the world. These projects have provided us with valuable data on the technology.

At first, it was thought that a fracture would be created based on conventional theories of hydraulic fracturing which predict the propagation of a single fracture caused by tensile failure of the rock mass. However, the Fenton Hill and Rosemanowes projects demonstrated that increases in permeability during hydraulic fracturing occurred mainly on existing natural joints and that shear slippage along these joints was the dominant mechanism. The word "stimulation" started to be used at Los Alamos National Laboratory instead of "fracturing" because of this mechanism.

The original concept was that once we knew how to create a HDR reservoir it would be a relatively easy task to duplicate this wherever there were hot crystalline rocks. The evidence from 20 years of research tells us that this idea was mistaken. The defining characteristics of an HDR reservoir are essentially functions of the natural jointing and its relation to the local stress field, which is beyond our control, together with the temperature and depth at which the reservoir is developed, which are largely our control. The development of HDR reservoirs must take this into account.

The mission of this Implementing Agreement is to address the issues currently necessary for the commercial development of HDR technology. It is important that the questions asked by potential developers be answered. It is believed that this cannot be done by any single experiment but by far the most efficient by drawing together the experience of HDR projects around the world.

Means:

The objectives shall be achieved by the Participants in the following Subtasks:

(1) Subtask A: Hot Dry Rock Economic Models.

The Participants will evaluate the economics of HDR systems worldwide by modeling the major parameters that affect the economics of HDR development, considering sustainability aspect and including a review of environmental and institutional factors.

(2) Subtask B: Application of Technology of Conventional Geothermal Energy to Hot Dry Rock Technology

Review of new and future development such as horizontal drilling, fracture mapping, pumping in conventional geothermal energy and determine their application to hot dry rock technology.

(3) Subtask C: Data Acquisition and Processing

The type and format of information necessary for the realization of a commercial HDR energy producing plant at each stage of reservoir design and development and of construction and operation of a HDR plant will first be identified and collected. The relevant results and parameter values are successively collated into a spreadsheet-like synoptic envelope, ready for use in the decision and design processing or where necessary, to await further refinement and completion.

(4) Subtask D: Reservoir Evaluation

Geochemistry (tracers and chemical reaction) and modeling techniques for HDR reservoir created by hydraulic fracturing/stimulation in different geological environments will be reviewed and evaluated. The extent to which reservoir characteristics can be determined by each techniques will be discussed.

Results:

Results of this Task will include:

(a) Analytical reports on economic and environmental data of HDR technologies, based on work under Subtask A; the reports shall be presented in special issues of international journals and at special sessions at international meetings;

(b) A report on conventional geothermal technologies applicable to HDR technologies, based on work under Subtask B.

(c) An international data base on the stages of development for commercial HDR plants, based on work under Subtask C;

(d) A analytical report on HDR reservoir evaluation technologies, based on work under Subtask D.

Possible Participants in this Task:

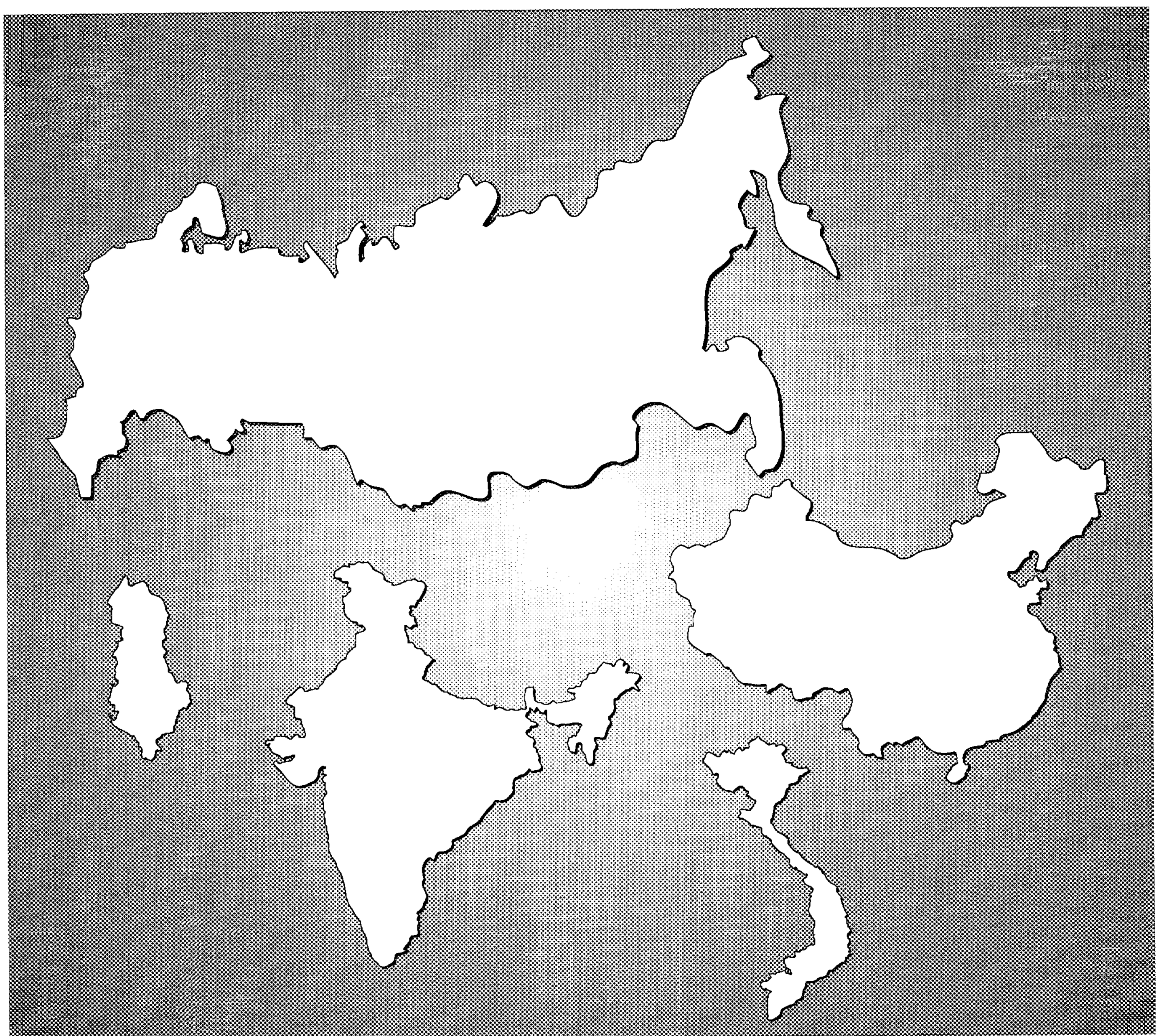
The Contracting Parties which are Participants in this Task may be the following:

New Energy and Industrial Technology Development Organization (NEDO)

United States Department of Energy

The Swiss Federal Office of Energy

Others



HOT DRY ROCK GEOTHERMAL POTENTIAL IN THE TECTONOMAGMATIC SETTING IN THE SOUTH CENTRAL VIETNAM GEOTHERMAL REGION

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Abstract

The South Central Vietnam geothermal region occupies an area of the Vietnam Territory from Quangnam - Danang through Raria - Vungtau. It is divided into three sub-regions with their characteristics of geological structure and tectonomagmatism as follow:

- Kontum geothermal sub-region was made up of an Archean crystalline basement which has been strongly broken by tectonomagmatic activities during Mesozoic - Kainozoic causing the formation of Mesozoic - Kainozoic depressional structures and a Holocene basaltic volcano arc. In this sub-region exist many geothermal systems expressed by 34 naturally - out-flown geothermal sources with surface temperatures up to 85°C.

- Danang geothermal sub-region contains depressional structures such as Triassic Nongson graben and Neogene Ainghia - Hoian basin, Tamky - Phuocson suture zone and younger intrusives of Paleogene granites, etc. Within the sub-region, many geothermal systems have been formed with 16 naturally-outflown sources having surface temperatures up to 71°C.

- Dalat Geothermal sub-region consists of two large structural zones: Dalat plutonovolcanic zone (Meso - Kainozoic) and a part of Srepoc zone (Mesozoic). These zones are typical for a part of an active continental margin (Andes type) in which many younger intrusions of alkaline granites and Holocene basaltic coverings have developed. This is also the area with many seismic activities and has 20 naturally-outflown geothermal sources with surface temperatures up to 83°C.

POTENTIAL HDR SITES AND PROSPECTS OF GEOTHERMAL ENERGY IN INDIA

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Due to the availability of large coal reserves,India is promoting coal based thermal power projects. Though several thermal power plants are in operation and several are being proposed,inherent problems related to shortage of fuel are affecting smooth functioning of the power plants. These problems include low coal production rates at the mine sites, shortage of wagons to transport coal to the plant sites and increase in demand for coal by cement,paper and steel industries.The estimated power shortage is of the order of 5000 MW and the projected power requirement for the next five years would be about 43,000 MW in addition to the present day production. Thus there is need to develop other energy resources and geothermal energy appears to be the alternative solution to meet this demand.

Indian geothermal provinces (Fig.1) are represented by high heat flow values and high geothermal gradients (Table 1).These values are similar to those reported over active rifts (Kenya: h.f.v = 101 mW/sq.m; Tanganyika: h.f.v.= 151 mW/sq.m).These provinces are associated with volcanic activity,rifting and subduction zones. More than 400 thermal springs issuing medium to high enthalpy fluids occur in these provinces.

At Puga, drill holes drilled (upto 300 mts.depth) by the Geological Survey of India,recorded temperature gradients much higher than those reported in table 1. The high temperature isotherms at such depths spread over an areas of about 7 sq.km. Precambrian gneisses have been encountered at the bottom of the drill holes. Since this province falls within an active subduction zone, prospects of initiating HDR based and natural geothermal fluid based power projects are bright. Tattapani geothermal site within the Narmada geothermal province is yet another such site. Presence of normal,reverse and thrust faults extending to depths of 300 mts.(within the Precambrian gneiss and schist) has been reported below Tattapani site (Ravishanker,1987). The estimated reservoir temperature of Tattapani geothermal site is as high as 215° C and the probable reservoir (Precambrian gneiss) depth is 3 km (Chandrasekharam and Antu,1995). Bore hole temperature measurements indicate that high temperature isotherms (120-200°C),at 1 km depth, spread over an area of 18 sq.km.

The Ganeshpuri geothermal site near Bombay (West coast) located in a volcanic terrain has an estimated lithospheric thickness of 18 km and the 1250° C isotherm has been encountered at shallow depth(Gupta et al.,1988). Several deep seated faults have been inferred in this region based on gravity and deep seismic sounding data interpretation (Chandrasekharam,1977; Pande and Negi,1987)

The continental lithosphere below the Cambay graben is thin and the Moho inferred to be at a depth of about 21 km. Mantle upwarping has been inferred in this region with the 1250° C isotherm lying at a depth of 21 km (Singh et al.,1991). Though this province shows anomalously high heat flow value and geothermal gradient (table 1), the estimated reservoir temperature of the Tuwa thermal spring lying on the eastern flank of the graben is about 150° C and the probable reservoir depth is 2.5 km. This reservoir could be a secondary reservoir and the probability of striking high enthalpy fluids at greater depths is high (Kamble,1993).

The Godavari graben with a thick Mesozoic-Proterozoic sedimentary cover over the Archeans is one of the most promising geothermal site in Andhra Pradesh. The power generating capacity of two thermal springs located in the NW part of the graben,estimated based on reservoir temperature, aquifer parameters and discharge rates, is of the order of 38 MW for a minimum period of 75 years (Jayaprakash 1995).

Thus the Himalaya,Narmada,Cambay and west coast geothermal provinces are suitable for developing HDR based and natural geothermal fluid based power projects while the Godavari gepthermal province is suitable for developing a natural geothermal fluid based power project.

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Table 1. Important geothermal provinces in India

Province	h.f.v.* mW/m	thermal* gradient °C/km	Surface temperature °C
Púga, Himachal Pradesh	650	100	67–80
Tattapani, Narmada	219	81	55–95
Cambay	83	70	55–85
Bombay offshore	83	78	
West coast	97	59	55–70
Godavari	104	60	55–58

* Data from published sources

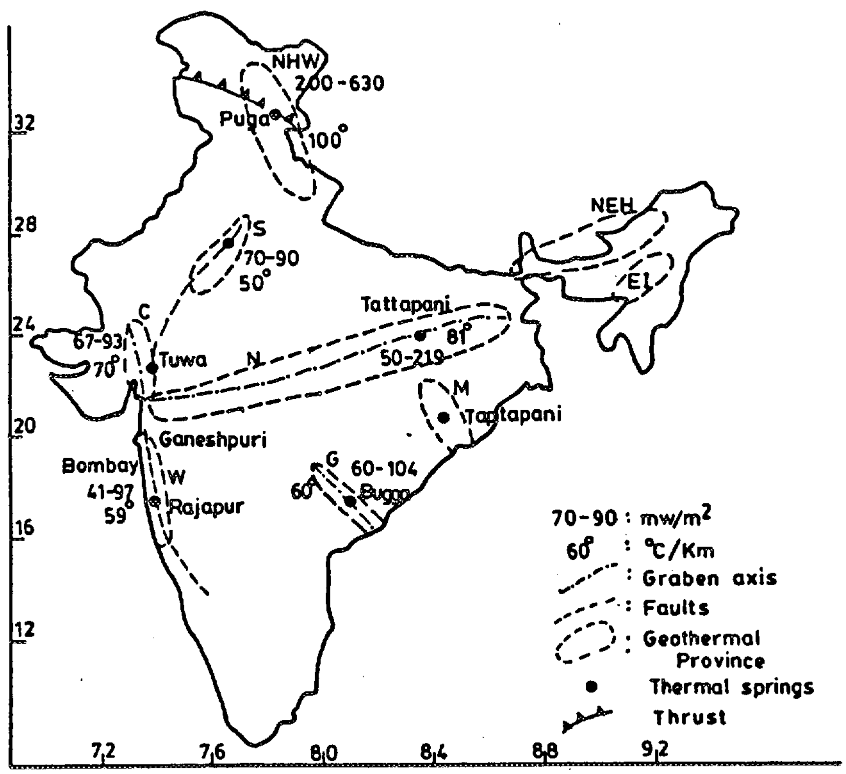

Fig. 1: Map showing a few geothermal provinces in India. Each province includes several thermal springs.

C - Cambay ; EI - Eastern India ; G - Godavari ;

M - Mahanadi ; N - Narmada-Tapi ;

NWH - North-West Himalayas ; NEW - North-East Himalayas;

S - Sohna ; W - West coast

ON POSSIBILITY OF HDR PROJECT IN NEAR-BY REGION OF PETROPAVLOVSK-KAMCHATSKY, RUSSIA

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The Kamchatka region possesses great geothermal resources. Nevertheless geothermal portion of total region heat and electricity energy production consists less than 5 percent. Most of Kamchatka operational geothermal steam and water fields locate in large distance from an administrative and industrial center of region -- town of Petropavlovsk-Kamchatsky. In the same time this town is main consumer of imported organic fuel (80 percent of region total).

Presently, geothermal energy is not used for heat and energy supply in Petropavlovsk. The geological and geophysical questions of possible use of heat of Avachinsky volcano (situated in 18 km distance from Petropavlovsk) formerly were discussed by S.A. Fedotov et al. (1977). Later the proposals for explore drilling in Avachinsky region were presented by G.N. Zabarny et al. (1983). In these works, on base of geophysical results, a temperature of about 250-500 Celcium deg. on 5000 m depth was predicted in a distance 6000 m from volcano.

By the financial reasons the drilling works in Avachinsky volcano region still have not conducted. Early conducted drilling works on the Petropavlovsk town territory have not positive results on geothermal water reservoirs. The measurement geothermal gradient in wells drilled before 1980 was less then "mean geothermal gradient" 30 Cel. deg./km (Polyak B.G. et al., 1965). The results of drilling of only deep well G-1 on town area in 1988 (Zabarny G.N. et al., 1990) show an absence of industrial geothermal water. Nevertheless wellbottom temperature (2500 m) was 62 Cel. deg. Water conductivity of permeable zone in G-1 well was determinate of 0.24 m*m/day. The works on drilling program 1986-1987 years, including 7 grounded point on town area, were stopped in 1988.

Presently, in new economic market conditions, a cost of imported fuel becomes increased. The aim of this paper is short discussion of economic benefit of possible use of the Avachinsky volcano heat by the standard HDR scheme for local town heating system as compared with traditional heat production technology. In addition economic effect of possible circulation geothermal system in town area is estimated.

1. Avachinsky HDR Heating System. For the simple estimation, the two wells HDR system with 8 MWt heat power is discussed. The drilling of two wells with 3000 m depth and creation of hydrofracture permeable zone between them is assumed. Production well flow is estimated of 10 kg/s with 220 Cel.deg. The pump pressure is evaluated of 10 MPa. Local cost of drilling is estimated to be $720/m (exchange rate 1 US$ = 5000 Russian rubles). The life period of the reservoir is assumed about 30 years. The results of economic evaluation of HDR heating system is presented in Table 1. As it turns out, the specific volcano heat cost is estimated of 16.4 US$/Gcal, 2.7 times less than current cost of fuel heat in town: 45 US$/Gcal for industry.

2. Petropavlovsk Geothermal Circulating System. The possible local town circulating system of two 3000 m wells in low permeability rocks with hydrofracture zone is discussed. The well head water temperature is estimated of about 70 Cel. deg. A system heat power is evaluated of 3,4 MWt. Drilling cost pump pressure are consider the same in above case. The production rate is assumed to be 20 kg/s. The result of economic evaluation of the system is present in Table 2.

The specific cost of the circulating system heat is estimated of 30 US$/Gcal, 1.5 times less than current cost of fuel heat in town: 45 US$/Gcal for industry.

Table 1. Estimated Cost of Avachinsky HDR Heating System

A. Capital cost, $1000	
Wells	4320.0
Pump (by Enting D.J. a.o., 1994)	70.0
Pipeline	2200.0
B. O&M Costs, $1000/year	
Field	594.0
Pumping	190.0
Specific heat cost, US$/Gcal	16.4

Table 2. Estimated Cost of Petropavlovsk Geothermal Circulating System

A. Capital cost, $1000	
Wells	4320.0
Pump (by Enting D.J. a.o., 1994)	70.0
Piping (by Enting D.J. a.o., 1994)	25.0
B. O&M Costs, $1000/year	
Field	223.0
Pumping	380.0
Specific heat cost, US$/Gcal	30.0

Thus both of discussed cases of HDR use for heat supply in Petropavlovsk town are profitable. Above simplified example and evaluation can be used for more detailed discussions and in making of decision for beginning HDR works in Kamchatka.

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THE SOURCES OF GEOTHERMAL ENERGY IN ALBANIA

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The Albanides represent the main geological structures that lie on the territory of Albania. They are located between Dinarites in the North and Helenides in the South, and together form the Dinaric branch of the Mediterranean Alpine Belt.

In Albanides there are spread rocks of the ancient age Ordovician and the newest age Quaternary. The structures of the Albanides are typically alpine. Recumbed, overthrusted and overtwisted structures are found, too. Generally their western flanks are affected by disjunctive tectonic. The Albanides are interrupted by deep longitudinal and transversal fault which affect the whole crust.

Albanides are divided in two paleogeographic zones: the Inner Albanides and the Outer Albanides. In the Outer Albanides there is situated the Albanian Sedimentary Basin with a thickness up to 15km. In the Inner Albanides there is the Ophiolitic Belt with a thickness up to 14 km, overthrusted over the Outer Albanides.

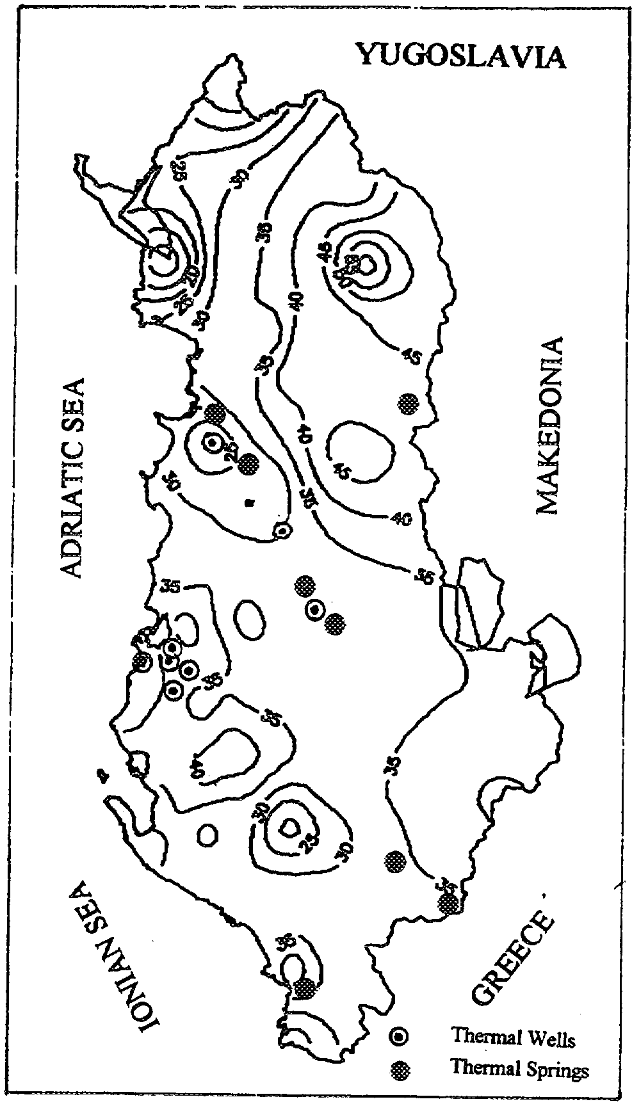
The temperature at a depth of 100m varies from 12 to 15°C and at a depth of 500m from 21 to 24°C. At 6000m depth in the center of Albanian Sedimentary Basin the temperature reaches values up to 105.8°C. In this basin the geothermal gradient has the average value of about 18.7 mK/m. Towards the East, in the Ophiolitic Belt the gradient reaches the maximal values of 32.2 mK/m.

In Albania there are some thermal sources whose temperature varies from 21 to 60°C. These thermal sources contain salt, absorbed gas and organic matters. They are of sulfide-methane, iodine-bromium, and sulfate types. These thermal sources are mainly near zones of regional tectonic fractures. Generally the water circulates through carbonate rocks. Hot thermal waters are found in deep oil and gas wells. These waters have temperatures up to 65.5°C.

The geothermal situation of Albanides offers two directions for the exploitation of geothermal energy, which is unused until now. Firstly, thermal sources of low enthalpy and of maximal temperature up to 80°C. These are natural sources or wells in a wide territory of Albania, from the South near Albanian-Greek boundary to North-East regions. Secondly, the use of deep single wells for geothermal energy like a "vertical earth heat probe". Numerous abandoned gas or oil wells can be used for geothermal purposes.

Actually in Albania has begun the study for the possibilities of exploitation of geothermal energy.

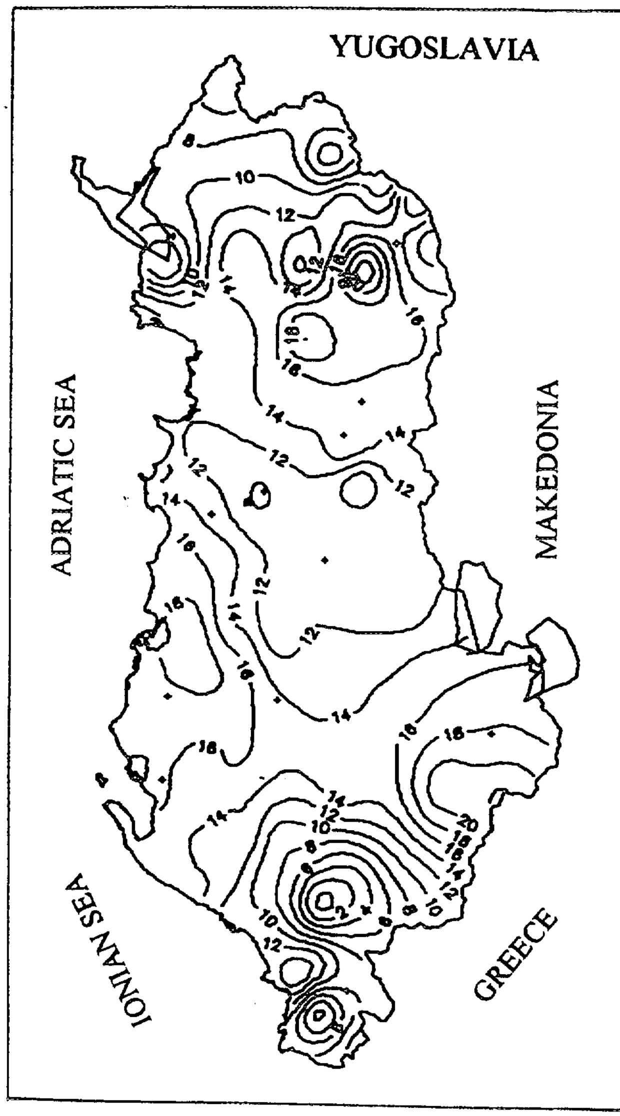
HEAT FLOW DENSITY MAP OF ALBANIA



Contour levels every 5 mW/m^2

SCALE 1 cm. = 25000 m

GEOTHERMAL GRADIENT MAP OF ALBANIA



Contour levels every 2mK/m

SCALE 1 cm. = 25000 m

ANALYSIS OF TECHNOLOGIES AND ECONOMICS FOR GEOTHERMAL ENERGY UTILIZATION OF THE ELECTRIC POWER PLANT. PART (III)

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INTRODUCTION

Geothermal energy -- it is a kind of heat energy,which pertained to interal heat of the earth.it was carried the heat through on the outward of the earth by the underground water of the rock section of the earth.in normally the temperature of the thermal water is 50-140°c.the people early know to use the geothermal water (energy) for the life.(such as heating, drying and etc.) but in the beginning of 19th century, it began to develop the industry.especially,in 70-80 years of 20th century, due to the industry and agriculture were rapid developed.so that quickly increased the need of large amount of the electric power. and now although there are coal power plant,oil and nature gas power plant,hydroelectric power plant and nuclear power plant,but all the countries of the world attached to prospect the geothermal power plant,it is the best economic saver(no consumption fuel) and no pollution environment power plant.
Since 1904 the Italy is the first established geothermal power plant in the world. soon afterward the U.S.A.,Iceland, Japan,Russia, New Zealand and etc.also established geothermal power plant.
in 1975 the U.S.A. geothermal power plant capacity of 522MW is the first in the world.and obtained good profits.in 1970 in China north of China,Jiangxi province,Guangdong province and etc,also established the geothermal power plant. at present,the most of the geothermal power plant are used the low boiling point working fluids.(such as butane,(C_4H_{10}),isobutane ($CH(CH_3)_3$),propane (C_3H_8) and etc.)their steam drive the turbine with generator.i.e. the principle of the thermodynamics--The Rankine cycle.
In China also used the low boiling point working fluid steam to drive the turbine and generator. as shown in Fig-(1).the most of the capacity of the turbine very small.(50-300KW/per single type) as we all know in this system,the thermal efficiency of the Rankine cycle is very low.(2-10%) and output work is also very small.(2.0-8.0KW/hr T thermal water,in which T=1000Kg)so that in 1992 ,1993 the present author's papers"Analysis of technologies and economics for geothermal energy utilization of the electric power plant" Part (I)* and Part (II)*dicussed and proved that:in the line diagram Fig-(1),the turbine is replaced by the turboexpander in geothermal power plant can be increased the thermal efficiency of the Rankine cycle(4-18%) and output work (15-40%).as shown in Fig-(2),the Rankine cycle of the geothermal power plant is used of 2-3 stages flashing evaporator,it can be increased above 10% output work and forced the heat transfer of the geothermal energy.

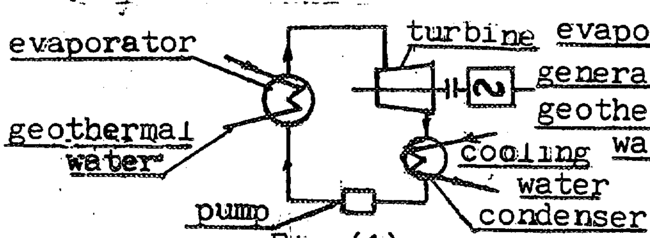

Fig-(1).

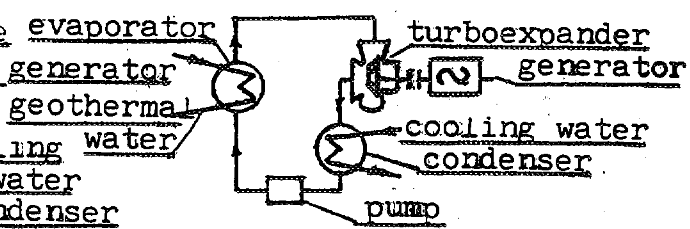

Fig-(2).

In this paper i.e. Part (III), the present author analysed and calculated the Stirling cycle and thermodynamics data and considered that:the Stirling engine can further to increase the thermal efficiency of the geothermal power plant and it is a high efficiency thermal engine.(thermal efficiency is 10-22%). Since 1815 Robert Stirling invented and developed the first Stirling engine.(working fluid:air,steam.)
In 1937-1978 Holand Philip Co,continuously devoted to research and develop the Stirling engine,it has had a great success and great break through.(began to use the working fluids:Hydrogen (H),Helium(He).)especially in 50-60 years of the 20th century the U.S. GE Co,German MAN-MWM Co and Sweden FFV & Kockums Co they researched and developed the Stirling engine one after another and also have had great success.especially developed large capacity about 100-530KW(125-690hp) Stirling engine and were used for the electric power plant,ship,automobile,tain and etc.at present the technologies and economics of the Stirling engine are advanced.due to their heating temperature at 600-650°c,so they thermal efficiency are very high.(30-35%). so the most of the countries of the world attached importance to the Stirling engine.we call this kind of Stirling engine high temperature Stirling engine.as following:we dicussed low boiling point working fluid Stirling engine their heating temperature at 50-200°c. i.e. we call the low temperature Stirling engine. the section of the Stirling engine and operating condition is shown in Fig-(3). the working fluid NH_3 or CO_2 (ammonia or carbon dioxide) was compressed in the expansion space.(i.e.Fig-(5)P-V diagram 1-2 constant temperature process),and the working fluid was heated by the heater (geothermal water).(i.e. Fig-(5) P-V diagram 2-3 constant volume process), while the NH_3 expand and the piston was forced downwards(i,e. Fig-(5) P-V diagram 3-4 constant temperature process) thereby turning grankshaft via the connecting rod.at same time there was a part of NH_3 was passed through the regenerator to the cooler, it was cooled.(i.e.Fig-(5)P-V diagram 4-1 constant volume process) and then into the compression space. due to the grankshaft and the flywheel turning and drive the piston and then the cooled working fluid was compressed again to pass through back to the regenerator and into expansion space. then it completed acycle.this is the Stirling cycle.and the same cycle was repeated.

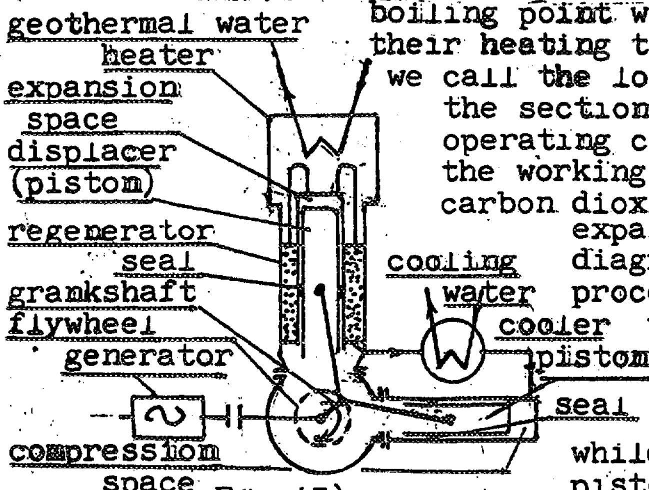

Fig-(3).

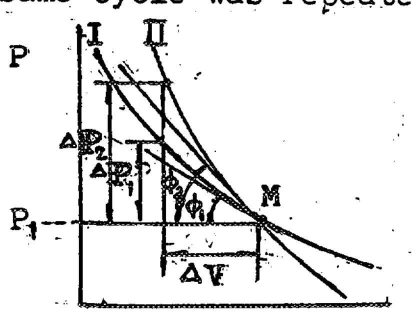

Fig-(4).

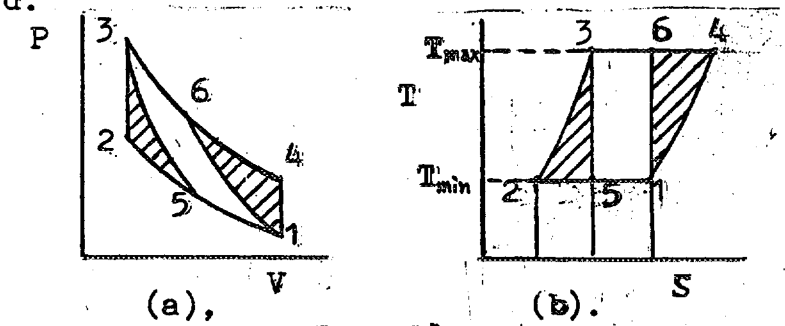

Fig-(5).

In Fig-(4). the curve I is expressed the constant temperature process's equation: $PV=nRT$. the curve II is expressed the isentropic process's equation: PV^{γ} =constant. we suppose that the curve I and the curve II meet at point M ,here we given: $P=P_1$ and given the curve I equation's derivative: $d(PV)=d(nRT)$ and the curve II equation's derivative: $d(PV^{\gamma})=d(\text{constant})$, then obtained: $PdV=0$ and $\gamma PV^{\gamma-1}dV=0$. i.e. the curve I: $\tan\phi_1 = P_1$ and the curve II: $\tan\phi_2 = \gamma P_1$. due to γ -- the ratio of specific heats at constant pressure, volume of the gas. $\gamma>1$ so $\phi_2>\phi_1$. thus it may be seen that: the curve I and the curve II, we change the same ΔV volume to do the work, which the pressure ΔP_1 is smaller than the pressure ΔP_2 .so the two curves of the constant temperature process(as Fig-(5). 1-2 and 3-4 curve) and the two curves of the constant volume process lines surrounded the area 1234. (Stirling cycle) and the two curves of the constant temperature process and the two curves of the isentropic process lines surrounded the area 1536. (as Fig-(5). 1-5 and 3-6 curve) this is the Carnot cycle. also is ideal cycle of thermal engine. as shown in Fig-(5)(a) and (b), at the same temperature condition: (T_{max} and T_{min}), we may be seen as following:

(1). area 1234 (Stirling cycle work) > area 1536 (Carnot cycle work).

(2). Carnot cycle thermal efficiency was proved from the Second Law of the thermodynamics $\eta_c = 1-(T_{min}/T_{max})$ (ideal thermal engine efficiency). but in here, the Stirling cycle thermal efficiency η_s also =Carnot cycle thermal efficiency $\eta_c = 1-(T_{min}/T_{max})$.

so above proved that: the Stirling engine is best thermal engine.

THERMODYNAMICS DATA OF WORKING FLUIDS FOR STIRLING ENGINE

The present author calculated and compared with thermodynamic data of the working fluids (H_2, He, air, NH_3 and CO_2) and considered that:

(20°c, 1 atm absolute)	H_2	He	air	NH_3	CO_2
density γ Kg/M³	0.0898	0.1785	1.29	0.771	1.976
specific heat C_p Kcal/Kg·°c	3.408	1.260	0.241	0.53	0.200
C_v	2.42	0.760	0.172	0.40	0.156
thermal conductivity λ Kcal/M·hr·°c	0.140	0.124	0.021	0.0185	0.0118
viscosity μ μP	84.2	188	173	91.8	137
cirtical temperature °c	-239.9	-267.96	-140.7	+132.4	+31.1
cirtical pressure atm P	12.8	2.26	37.2	111.5	72.9

the ammonia NH_3 was applicable for the low temperature Stirling engine. (at t=70-110°c, P=60-110atm) and the carbon dioxide CO_2 was applicable for the low temperature Stirling engine (at t=100-150°c, P=70-150atm). the value μ, C_v and γ of the ammonia is smaller than the carbon dioxide, so the ammonia heat transfer is better than the carbon dioxide. (due to the Re↓ of the ammonia)and the friction loss ΔP is also small.

ANALYSIS OF TECHNOLOGIES FOR DESIGNED THE STIRLING ENGINE

The present author calculated and found that: the Stirling engine at high temperature and high pressure (at t=600-650°c

P=100-200atm) designed and calculated the volume of the cylinder, it may be used the modified constant temperature expansion formula.i.e. the work: $L=BP_2 \cdot V_2 \cdot \ln P_1/P_2$. here the B--modified coefficient.due to the high temperature Stirling engine, the working fluids are not the ideal gases.the present used of Stirling engine capacity(2-690hp), working fluids(H_2, He).and found that: B=0.028-0.088.it is feasible. as shown following:

type	L hp	bore stroke	P_{max} lb/in^2	B	type	L hp	bore stroke	P_{max} lb/in^2	B
10-36	7.47	2.362in	1000	0.038	Philip	120	3.26in	1720	0.049
GPU-2	7.3	2.375"	1000	0.038	Philip	200	3.26"	3140	0.054
GPU-3	11.2	2.75 "	1000	0.034	GMR	148	4.0 "	1500	0.049
3015	40	3.47 "	1560	0.046	GMR	129	4.0 "	1500	0.056
4s1210	380	5.70 "	1500	0.061	GMR	2	1.18"	1500	0.054
1-s1050	75	5.70 "	1436	0.073		22	1.57"	1500	0.043
2w17A-	138	6.50 "	1100	0.088		690	3.40"	3500	0.028

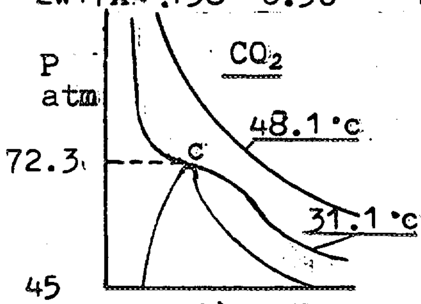

Fig-(6).

the low temperature Stirling engine(at t=70-150°c, P=60-150atm) the working fluids NH_3 and CO_2 at thermodynamics P-V diagram, the PV curves may be considered approximate the ideal gases(the temperature of gases must be over the cirtical temperature)so it could use the formula: $L=P_1 V_1 \ln P_1/P_2$, in here B=1.this is the constant temperature process.(as shown in Fig-(6).) as an example: 300KW Stirling engine (working fluids CO_2 or NH_3)diameter of the cylinder is 50-60cm.(single cylinder).

the present author compared with the 300KW turbine (70cm turbine disk) and 300KW Stirling engine(designed):the weight of main and auxiliary equipments, working fluid, cooling water comsumpation and overall dimensions are far larger than the Stirling engine, so it is the save and economic investment. the Stirling engine payback period $\leq$ 1.5-2 years.the turbine power plant payback period $\leq$ 2.5-3 years.(as China condition)

CONCLUSION

1. the working fluids NH_3 or CO_2 are used for the low temperature Stirling engine, it is possible.
2. the formula $L=BP_2 \cdot V_2 \ln P_1/P_2$, and suppose that B=1, which use to calculate and design the volume of cylinder of the low temperature Stirling engine it is feasible.
3. the low temperature Stirling engine is high thermal efficiency and economic thermal engine.
4. the present author suppose that: B=1, remain to further improve after operating.and the regenerator may be frozen at operating, it need to forced insulate.

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